Universidade de Aveiro
2016/2017

Departamento de Ambiente e Ordenamento

Rita Meireles Mendonça

Assessing the effectiveness of economic instruments to steer urban sprawl: a hedonic pricing simulation modelling approach

Avaliação da eficiência de instrumentos económicos no controlo do urban sprawl: uma abordagem de simulação de preços hedónicos

Universidade de Aveiro
2016/2017

Departamento de Ambiente e Ordenamento

Rita Meireles Mendonça

Assessing the effectiveness of economic instruments to steer urban sprawl: a hedonic pricing simulation modelling approach

Avaliação da eficiência de instrumentos económicos no controlo do urban sprawl: uma abordagem de simulação de preços hedónicos

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Gestão e Políticas Ambientais, realizada sob a orientação científica do Professor Doutor Peter Roebeling, Equiparado a Investigador Auxiliar no Departamento de Ambiente e Ordenamento da Universidade de Aveiro e coorientação da Professora Doutora Filomena Martins, Professora Associada do Departamento de Ambiente e Ordenamento da Universidade de Aveiro.

O júri

Presidente

Prof.ª Doutora Myriam Alexandra Lopes
Professora Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro.

Prof.ª Doutora Margarita Matias Robaina
Professora Auxiliar do Departamento de Economia, Gestão e Engenharia Industrial e Turismo da Universidade de Aveiro.
(Arguente)

Prof. Doutor Peter Cornelis Roebeling
Equiparado a Investigador Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro.
(Orientador)

Agradecimentos

Ao meu orientador, Prof. Doutor Peter Roebeling, pela oportunidade, incansável apoio, acompanhamento constante e por toda a aprendizagem que me possibilitou, contribuindo imensuravelmente para o sucesso desta dissertação.

À minha coorientadora, Prof.ª Doutora Filomena Martins, pelos conselhos valiosos para a presente dissertação.

À minha mãe e avó, que sempre acreditaram em mim e nunca me deixaram desistir, possibilitando que chegasse até aqui.

Ao Ricardo, pelo apoio e acompanhamento incansável, pela preocupação e força.

Às minhas amigas, Bruna, Catarina, Francisca, Marta e Tita, por serem tudo aquilo que eu precisei durante o ano, pelos conselhos, apoio e momentos de descontração, sem nunca me deixarem desistir. Sem vocês este ano não teria sido nada assim. *You are unforgettable*.

Às minhas amigas Márcia, Sara e Xixo, por me terem acompanhado e apoiado nos momentos mais difíceis e me conseguirem dar uma perspetiva diferente quando eu mais precisei.

Palavras-chave

Dispersão urbana; Imposto de propriedade; Imposto sobre o terreno; Modelo de simulação de preços hedónicos; Subsídio de transportes públicos

Resumo

Nos últimos séculos, as cidades sofreram grandes alterações que levaram a um processo de urbanização global. Um dos fenómenos decorrentes desta urbanização é o *urban sprawl* (dispersão urbana), que pode ser definido como uma expansão do tecido urbano da cidade em direção aos subúrbios. O decréscimo dos preços de habitação, dos preços de transporte e a falha em internalizar os valores reais do solo (os preços de terrenos são demasiado baixos) originou um realojamento da população para a periferia das cidades, o que resulta em padrões de urbanização fragmentados e de pouca densidade, apresentando inúmeros impactos negativos. A consciencialização para este problema levou à necessidade de identificar e avaliar políticas eficientes para conter este fenómeno, incluindo abordagens institucionais, instrumentos de comando e controlo e instrumentos económicos de incentivo. No entanto, os dois primeiros têm sido considerados insuficientes para o controlo do *urban sprawl* e não existem muitos estudos que avaliem a eficiência dos instrumentos económicos de incentivo. Assim sendo, o objetivo do presente estudo consiste na avaliação de diferentes instrumentos económicos de incentivo no controlo do *urban sprawl*. Com esse propósito, o modelo SULD (*Sustainable Urbanizing Landscape Development)* é utilizado para testar a eficiência de um imposto de propriedade (único e linear), um imposto sobre o terreno (único e linear) e um subsídio de transportes públicos (disponibilizado para residentes de baixo rendimento e a residentes de rendimento baixo e médio), que foram avaliados como ferramentas de controlo deste desenvolvimento desmesurado. A cidade de Aveiro (localizada no Centro de Portugal) é apresentada como caso de estudo. Analisando os resultados obtidos, é possível concluir que o imposto de propriedade e o subsídio de transportes públicos resultaram numa contração da cidade enquanto que o imposto sobre o terreno não obteve alterações e causou até alguma expansão. Assim sendo, o imposto de propriedade (constante aumento de 10% e linear 5%-10%) e subsídio de transportes públicos providenciado para grupos sociais de rendimentos baixos e médios demonstram ser os instrumentos mais eficientes, ao contrário da taxa sobre o terreno, que se apresenta como o instrumento menos eficiente no controlo do *urban sprawl*.

Keywords

Hedonic pricing simulation model; Land tax; Property tax; Public transport subsidy; Urban sprawl

Abstract

Over the past centuries, cities have undergone through major transformations that led to global urbanization. One of the phenomena emerging from urbanization is the uncontrolled spread of cities into undeveloped areas – i.e. urban sprawl. The decrease in housing and commuting costs as well as the failure to internalize the real costs of natural land, encouraged households to move to the urban fringe – resulting in fragmented, low-density urban development patterns with multiple negative impacts associated. Awareness of this problem encouraged the identification and assessment of policies against urban sprawl, including institutional approaches, command and control instruments, and economic incentive instruments. However, institutional approaches and command and control instruments have been proved inefficient in steering urban sprawl and there are only few studies that assess the effectiveness of economic inventive instruments. Hence, the objective of this study is to assess the effectiveness of economic incentive instruments that aim to enhance urban sustainability as well as contain urban sprawl and associated negative impacts. To this end, the Sustainable Urbanizing Landscape Development (SULD) model is used to assess the effectiveness of a property tax (flat and linear), a land tax (flat and linear) and a public transport subsidy (provided to low income households and to both low and middle income households). A case study is provided for the City of Aveiro in Central Portugal. Results show that a property tax leads to the contraction of the city, a land tax to no alterations and even some expansion, and a public transport subsidy to the contraction of the city. Overall, the property tax (flat 10% and linearly increasing 5%-10%) and the public transport subsidy (for low and middle income households) are the most effective instruments while, on the other hand, the land tax is the least effective instrument to control urban sprawl.

Index

Figure Index

Table Index

Annex Index

1. Introduction

1.1. Theoretical Context

1.1.1. Urban sprawl

Sustainable development is a wide and dynamic process based on growth that provides an improvement in societal welfare, environmental protection and economic development, and that meets the needs of present and future generations (Hassan and Lee, 2015). Currently more than half of the world's population lives in cities, a lot more than the 10% registered in 1990, and around 85% of the Gross Domestic Product (GDP) in the European Union is produced in cities (EEA, 2006a, 2013a; Irwin *et al.*, 2009; Silva, 2016). Therefore, sustainable development is considered an overarching goal for countries' socio-economic development in a holistic way and very important in urban planning.

Over the past centuries, cities have undergone through major transformations that led to global urbanization. This is one of the most complex processes concerning land use, mainly due to technological development that encouraged the mechanization of labour-processes, the reduction in transport costs and, consequently, changes in people's preferences (Haase and Schwarz, 2009; Irwin *et al.,* 2010). All these factors greatly affect the way cities are organized and land use changes (i.e. purpose associated with humans' exploitation of the land cover, Lambin *et al*., 2000) are a major indicator of the way the environment is influenced by mankind (Pinto, 2008). Urban systems are influenced both by social as well as natural components, existing multiple linkages between the environment, land use and human sphere. Humanity has been changing land since its existence, as population growth lead to the progressive occupation and construction for residential purposes as for transportation, recreational and industrial ones, which undoubtedly poses numerous impacts on the environment and all its components. All these patterns evolved to a point that planning became a necessity to minimize the impacts on natural systems while allowing Human evolution (see Fig.1) (Haase and Schwarz, 2009).

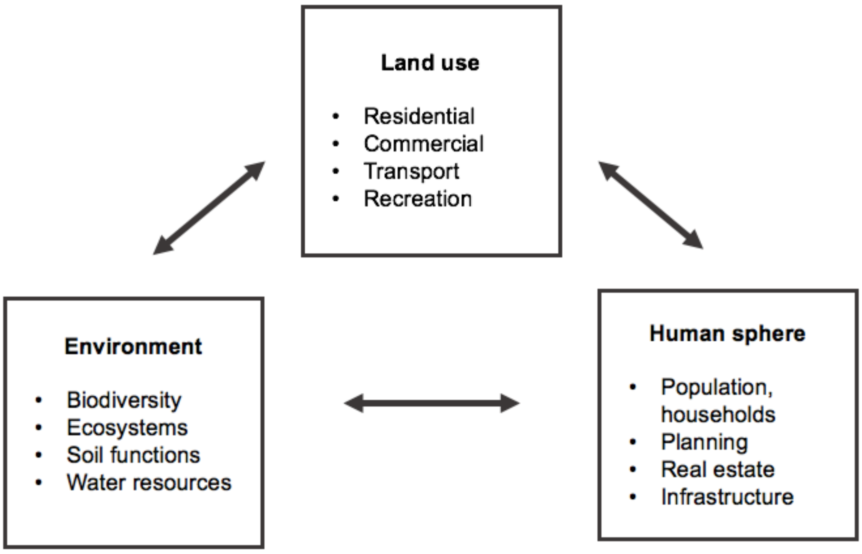


Fig.1. Linkages between different aspects and their variables concerning the urbanization process (adapted from Haase and Schwarz, 2009).

One of the phenomena emerging from these interactions is urban sprawl. Urban sprawl can be defined as "the physical pattern of low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas" (EEA, 2016, p.20), the "uncontrolled spread of towns and villages into undeveloped areas" (FOEN, 2015), the "unplanned and uneven pattern of growth, driven by multitude of processes and leading to inefficient resource utilization" (Bhatta *et al.*, 2010, p.731) or the "uncontrolled, scattered suburban development that increases traffic problems, depletes local resources, and destroys open space" (Ji *et al.*, 2006, p.62). Thus, a sprawled city has non-compact features and a medley of land uses on the urban fringe, as the developed area spreads through the city limits due to, usually, poorly planned development (EEA, 2006b; Irwin and Bockstael, 2004; Song and Zenou, 2006). Urban land uses replace natural and agricultural land uses, resulting in a new landscape with city features – including housing, infrastructures and industrial activities (see Alves (2014) and Pinto (2008) for an overview).

This scattered urban expansion has multiple and complex, economic (macro/microeconomic, transport), biophysical (city centre problems and environmental amenities), social (demographic, housing preferences) and institutional/governance (legal framework) causes (see Table 1 for a synthesis). Households have the desire to move towards the suburbs for several reasons, as the possibility to improve their housing quality, the inappropriate housing, garden sizes or poor environmental quality on city centres, and quietness of the neighbourhood as well as the possibility to have detached and larger houses with more green space (Couch and Karecha, 2006). Furthermore, the lower price of agricultural/peripheral land for construction (reducing the cost of living), the willingness to live near green or blue spaces (usually located outside the city core and in coastal areas), and the option to use these desirable places for tourism. In fact, Wu (2006) argues that that the ultimate cause of this decentralization is the consumer demand for suburban amenities, which means that land near any valuable feature will be more intensively used (Pinto, 2008). Nevertheless, from an economic point of view, the main reason consists on non-accounted costs in transportation, development and housing sectors (Bento *et al.,* 2005; Kulmer *et al.,* 2014). Likewise, increases in income, decreases in commuting and housing costs, and improvements in road infrastructures (new build-up land is usually dependent on transport infrastructures) and poor quality of public transport and city centre conditions deterioration have encouraged residents to live further from urban centres (Alves, 2014; EEA, 2006b, 2016; Kulmer *et al.,* 2014; Poelmans and Rompaey, 2009; Silva, 2016). Population growth can be a reason for urban sprawl since more space is required for its settlement, increasing the urbanized limits. However, sprawl is also observed when there is a decline in population, which is a concern as natural-artificial land conversion is taking place at a higher rate than population increase, especially in coastal areas (Cotteller and Peerlings, 2011; EEA, 2006a; Pinto *et al*., 2009). All these factors lead to the desire to move to and construct in suburban and rural environments, allowing a different lifestyle while maintaining the same accesses and advantages of living in the city centre.

Table 1. Factors associated with urban sprawl (adapted from EEA, 2006b).

Dimension	Causes
Macroeconomic	Economic growth Globalization European integration context
Microeconomic	Income raise Land price Cheap agricultural soil availability Competition between cities
Demographic	Population growth Family number raise
Housing preferences	Housing space Location preferences
City centre associated problems	Poor air quality Noise Small houses Insecurity Social problems Green and blue spaces shortage School quality
Environmental	Environmental amenities (location, quality)
Transport	Private car ownership increase Road infrastructures Low fuel prices Poor quality of public transport
Legal framework	Poor urban planning Not effective application of existing programmes Lack of cooperation between different agents

The low price attributed to land, that encourages sprawl, is directly related to the valuation that is given to that open space, especially as the most wanted areas are the ones that are more valuable (EEA, 2006a). Ecosystems provide a wide range of different services that are essential to human well-being, including provisioning services (that include all goods that can be directly harvest and used such as food and energy), regulating services (such as soil carbon sequestration, flood regulation and pollution dissolution) and cultural services (that include aesthetic and recreational features) (Groot, *et al.*, 2012). Ecosystem services, degradation and replacement costs are, however, not fully considered and, hence, cheap construction and land conversion takes place – resulting in over-exploitation and resilience reduction of the ecosystems. Land costs would be multiple times higher if these services were fully taken into consideration (even in more conservative studies, the value attributed to ecosystem services was considered to be about 125 trillion dollars/year) (Constanza *et al*., 1997; Groot, *et al*., 2012). Therefore, these ecosystem services are not entirely accounted in markets (around 80% excluded), and as current valuation methods are based on these prices, planning decisions do not account non-market values. From an economic point of view, this gap between the prices paid and the real social costs result in an externality, which means that the situation cannot be considered economically efficient (Constanza *et al*., 1997). To ensure a more sustainable land management, the true social value that these services generate should be considered as to minimize the effects related to urban expansion and making the most of the already converted spaces not to compromise more services and thus its associated benefits (Groot, *et al*., 2010).

There are multiple, positive and negative, effects accruing from urban sprawl (EEA, 2016). In fact, this type of development has cumulative consequences as the alterations are gradual, mostly because noticeable impacts in landscape surroundings take time. It can be argued that it is a natural process and a direct result from population and economic growth – preventing the preference of the population to move outside the city being, in that perspective, harmful to the economy. In the same way, living in a suburban or rural area is correlated with less noise and pollution as well as less stress related to traffic congestion and overcrowded areas. It is also considered better for children, as they have more space to develop and have more contact with green and blue spaces (EEA, 2016). However, there are multi-negative environmental, social and economic impacts that are interconnected:

- Environmental: Urban sprawl involves, firstly, the consumption of numerous natural resources (such as land and soil for construction) that are non-renewable at a human scale (EEA, 2006b, 2016; Silva, 2016). Secondly, it involves the destruction of the natural landscape and, therefore, the loss of conservation targets, habitats and hence, biodiversity, ecosystems and associated services as well as soil fragmentation. Thirdly, it involves impacts on climate change since soil destruction will decrease its carbon sink capacity and the new constructed areas will imply more construction of transport infrastructure, basic services and energy consumption (more compact cities are more energetic sustainable- Alves, 2014), and, consequently, more greenhouse gas emissions (EEA, 2006b, 2013a, 2016; Lambin *et al*., 2000; Silva, 2016). Finally, coastal areas, that can be considered finite resources, are also severely affected by the existent intensive use (see Pinto (2008) for a more detailed overview) as groundwater quality and quantity are reduced, matter flow is hampered, waste treatment becomes more difficult and flooding risk is increased, which threatens entire populations (Alves, 2014; 2006b; EEA, 2016; Haase and Schwarz, 2009; Sutton, 2003).

- Social: At the social level, urban sprawl leads to a larger tendency for segregation based on income, increased stress and health problems related to higher levels of air pollution and noise due to traffic congestion/longer commuting trips (half of the European population is exposed to high levels), reduction in social interaction and recreational activities due to larger distances, and concerns related to crime and education (Milan and Creutzig, 2016; Haase and Schwarz, 2009; Sutton, 2003; Wu, 2006). Quality of life is diminished for present and future generations, due to the loss of ecosystem services and cultural legacy. Furthermore, the increased time spent travelling, which leads to less free time to perform desired activities, contributes to an inactive-lifestyle and, for that reason, is welfare damaging. Finally, the loss of agricultural land to residential and industrial areas increases the dependence on imported food, which can have less quality and might contribute to ascendant conflicts resulting from competition for resources (EEA, 2016).
- Economic: Urban sprawl is, oftentimes, seen as economically beneficial by agents inasmuch as many costs are not taken into account – i.e. many costs are externalised, such as the environmental, social and health costs, being the paid costs smaller (EEA, 2016). In fact, it is estimated that around 100 billion euros are lost because of traffic congestion, while drivers underestimate the real costs of car use, travelling larger distances because of that (only consider fuel instead of also maintenance and the automobile depreciation costs, etc., EEA, 2013a). Thus, urban sprawl is associated with higher commuting costs for households who must travel great distances, raising congestion and public transport expenses, fiscal disparities between communities, increasing expenditures in public services' costs and taxes – augmenting transport infrastructure construction and maintenance costs, reducing investments in degraded areas, and lowering house prices (EEA, 2006b; Wu, 2006). Households must also pay for additional costs that distribution companies (water, communications, energy) must bear to bring those services to more remote locations (Alves, 2014; UA, 2011). Increased car dependency leads to higher maintenance and fuel costs as well as health deterioration and, hence, larger insurance and services expenses. Furthermore, shop closure and job displacement in the cities' centres can lead to some households' income depletion and overall degradation of these areas (Alves, 2014; EEA, 2016).

Urban sprawl is a growing concern among the most diverse countries. Despite being an originally United States problem, Europe land use patterns have become similar. EU cities were characterized by compact urban centres until 1960s, trend that changed mainly due to the economic growth and modern transport systems patterns after that period (EEA, 2006a; Poelmans and Rompaey, 2009). In fact, it is expected that approximately 80% of the European population will be living in urban areas by 2020, so urban sprawl is a fast-growing problem with no apparent slowing down (Bhatta *et al.*, 2010; EEA, 2006b; Haase and Schwarz, 2009). The problem is more severe in southern, eastern and central Europe (EEA, 2006b; Wu, 2006). For these reasons, the European Union has come up with several programmes and measures aiming to tackle urban sprawl and to promote sustainable land use (EEA, 2006a, 2016).

This scattered development has deep negative and significant impacts in coastal areas, that are considered more appealing and with significant amenities. This leads to exacerbated population growth and land conversion into artificial uses and, as a consequence, to population densities that are ~10% higher and artificialized areas that are ~25% larger as compared to inland areas in European countries, which corresponds to about 75% of the European population living in coastal areas, value that is estimated to rise within the next years (see Fig.2.a)); (Pinto, 2008). Portugal's rapid economic growth (one of the biggest of EU), urban development, highly populated coastal area (see Fig.2b)) and economic dependence on tourism, lead to the occurrence of urban sprawl. In fact, in 2000, about 50% of Portugal's urban areas and 75% of the population were located within 13 km of the coastline. Due to the high pressures on these areas, they are subject to special development and legal measures (EEA, 2006a, 2006b; Fidélis and Roebeling, 2014; Pinto, 2008). However, the current growth and occupation patterns in Portugal put at stake its sustainable development (Prates and Melo, 2007).

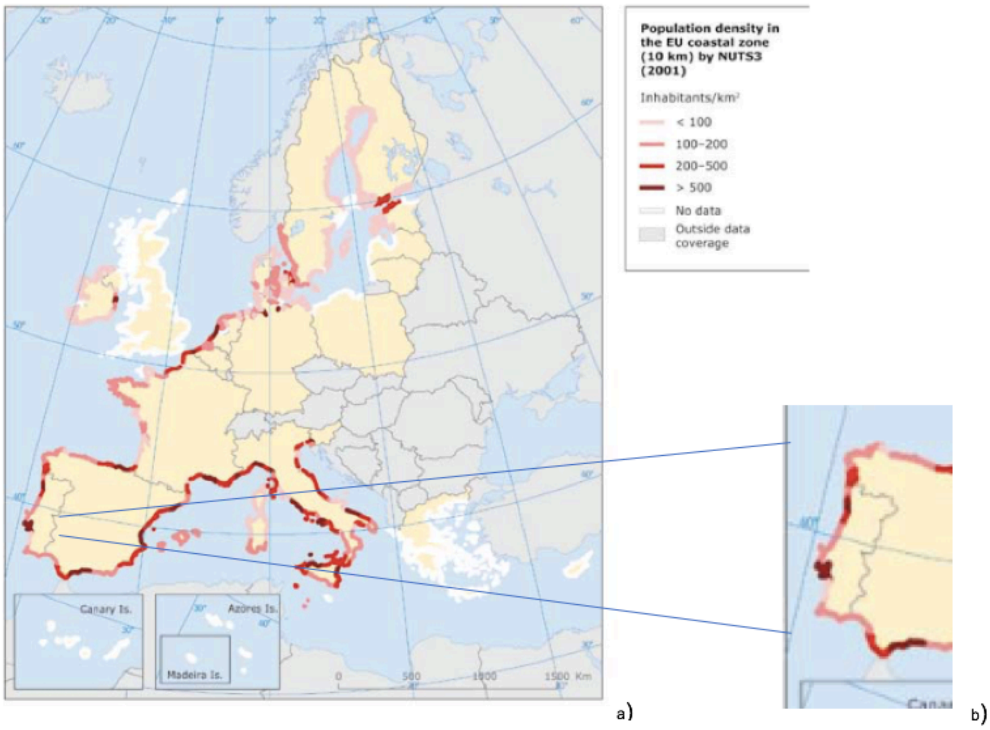


Fig.2. Population density: a) in European coastal zone (0-10 km), 2001; b) in Portugal coastal zone (0-10 km), 2001 (adapted from EEA, 2006a).

1.1.2. Policies

Despite the fact that the awareness about urban sprawl is expanding and that most land developments are regulated, it still leaves much to interpretation since land use planning is complex and have severe shortcomings in most European countries (EEA, 2006a; Milan *et al.*, 2016; Silva *et al.,* 2012; Wu, 2001). There are problems related to planning, existing policies that lack integration and institutions that fail in giving the actual importance to the inclusion of economic, social and environmental perspectives in order to achieve a sustainable management (EEA, 2006a; Pinto, 2008). Policies can either enhance sprawl or support its containment. Investments in new motorways will increase the development along its way, exacerbating urban sprawl; nevertheless, if this investment is channelled to the outgrowth and reform of the deteriorating city's cores, more compact cities would be encouraged (EEA, 2006b). Therefore, deeper understanding of the relationships between policies and urban sprawl is imperative in order to minimize its adverse effects, recognizing that these policies should not be incompatible with growth measures (Henning *et. al.,* 2015; Wu and Platinga, 2003). The measures and instruments to minimize urban sprawl rely on the cooperation between different levels of legislative institutions and different stakeholders, to accomplish sustainable, cohesive and integrated strategies. This effective management is hampered by the fact that often management issues are distributed along several levels of administration (EEA, 2006b). In fact, policies can have both direct effects (influencing the landowner's benefits or costs) and indirect effects (through externalities) that need to be accounted for in order to predict its effects. Hence, policies must be improved to promote stability and fairness (EC, 2014; Irwin and Bockstael, 2004; Perman *et al.,* 2003).

The European Union has the objective that, by 2020, all parties will be implementing policies for sustainable urban planning (EEA, 2016). To this end, use can be made of institutional approaches, command and control instruments, and economic incentive instruments (Perman *et al.,* 2003):

- Institutional approaches: these entail the legal framework, that can impose restrictions, make classifications or recommendations, as well as specifying liability. So, they constitute the base and rules upon which decisions and actions are taken. They are essential to create guidelines, principles and aims on which decision-makers rely and are, in theory, efficient in allocating resources. However, this allocation relies on some market assumptions that usually are infeasible, and institutional approaches usually are generic and not very clear, so they should be periodically revised and other instruments are necessary, especially in the environmental area in order to achieve the pretended goals. (Almeida *et al.,* 2013; Fidélis and Roebeling, 2014).
- Command and control instruments: these are the traditional instruments that are based on rules, regulations, obligations and restrictions – thus imposing or limiting certain types of behaviour, quantities or qualities. This means that awareness is not fomented and there is the need for monitoring and control to assure that the requirements are fulfilled. Despite promoting known quantity outcomes, these instruments do not increase revenues neither encourage technological development or innovation. Despite compelling, command and control instruments are not market-based, so the external costs remain unconsidered, meaning that they might but usually are not economic efficient (Kulmer *et al.,* 2014).
- Economic incentive instruments: these instruments are designed to encourage and promote more sustainable behaviours. Thus, agents are compelled to change instead of being forced to, which implies no monitoring and thus, less costs associated with its implementation and follow up. They can simply be information instruments that aim the transparency and promote awareness of the consumer, which can be included in all the

others (EEA, 1999). Moreover, market-based instruments can be used, which includes taxes, charges, subsidies and marketable permits. These allow the independence of agents and their efficient and sustainable voluntary actions are encouraged, as well as the technological development. Market-based instruments increase revenues, that can be dislocated to reduce other taxes and internalise the external costs so as to attain economic efficiency (EEA, 2006c).

Urban sprawl can be seen as a failure to internalise all social costs regarding land value and, for that reason, productive landscapes are neglected and converted into non-natural ones, and that is why some effective instruments must be found (Groot, *et al*., 2010). Traditional policies might not be the most effective, as they were not designed for environmental purposes, leading to the necessity to study new approaches. Various economic incentive instruments can be considered for controlling urban expansion towards the suburbs as well as penalizing further development. Firstly, increased housing costs, through a property tax, might constitute a great tool to curb urban expansion towards the city suburbs, since households will have less incentive to buy larger houses that will be much more expensive and that usually are located outside city centres, where there is more space available and land is cheaper, thus restricting urban sprawl (Perman *et al*., 2003; Tscharaktschiew and Hirte, 2011). Accordingly, a land tax, aiming the consideration of land real costs for developers and households, can be efficient in controlling urban sprawl, which happens on behalf of the low price attributed to agricultural land, that promotes the conversion of natural land to artificial uses (Milan and Creutzig, 2016). Additionally, transportation is a key point for economy, society and for sprawl, being essential to readdress its sustainability and to reduce the associated externalities. Thus, the external costs imposed on society and environment should be accounted (Potter *et al*., 2006). Even with the technological development, the fact is that this sector has not yet been drastically changed, being expected that congestion costs will raise 50% until 2050 (EC, 2011). For that reason, effective measures must be found, as public transport subsidies, that consist on direct or indirect payments/ payments reliefs to the associated fares, aiming to reduce services' revenues and consumers' costs, hence to discourage private car use and highway construction as well as the reduction of the associated externalities, as congestion and emissions (EC, 2011; Potter *et al*., 2006). In short, proper financing instruments' studies are imperative, to redress urban sprawl and to include total value arguments in city planning (Groot, *et al*., 2010).

Notwithstanding, for any of these instruments to be effective they must be well-planned, the intentions must be transparent and the population affected must be correctly informed and included in the process to minimize objections and misinterpretations. It is now acknowledged that there is not one best instrument but, instead, an efficient association between more than one of them might be more suitable (EEA, 2006c, 2010). Moreover, a tax shift from more to less distortive taxes, such as the environmentally-related, has already been a part of policy recommendations in "Europe 2020" (EEA, 2013b).

The use of economic incentive instruments has become more widespread since the 1970s, and may form an efficient and effective alternative to command and control regulations (that usually are not cost-effective). From an economic perspective, the leading reason for excessive urban sprawl is unceasing market failures in the transport sector, the housing market and in assessing the benefits of ecosystem services – thus leading to inefficient urban planning strategies (Bento *et al.,* 2005; Kulmer *et al.,* 2014). One of the measures to correct these market failures, and thus to control this non-contiguous development, is with economic incentive instruments – aiming the full internalisation of the social costs and benefits from alternative urban planning strategies (Bureau, 2012; Henning *et. al.,* 2015). These economic incentive instruments are remarkably important in shaping land use and, consequently, urban sprawl, as they encourage eco-friendly behaviour with benefits for the economy while they also have a self-regulatory force (EEA, 2010; Perman *et al.,* 2003). These policies have proven that they can tackle urban sprawl and help to redress the market failures that drive it, enhancing more compact-urban-green features within the cities (EC, 2014; Peng and Wang, 2009).

1.2. Objectives

The overall objective of this study is to assess the effectiveness of economic incentive instruments that aim to enhance urban sustainability as well as to contain urban sprawl and its associated negative impacts. To address these questions, a property tax, a land tax and a public transport subsidy are evaluated using the Sustainable Urbanizing Landscape Development (SULD) model, which is based on classic urban economic models with environmental amenities. A case study is provided for the City of Aveiro, a medium-sized city in central Portugal, so that more informed decisions can be attained and in a way that replication can be achieved, as integrated land management relies on the enlargement of base knowledge and information.

Accordingly, the following specific objectives are defined:

1. Literature review on environmental-economics of urban change;
2. Review of integrated (spatially explicit) environmental-economic urban planning models;
3. Description of and data collection for the City of Aveiro case study;
4. Application of and scenario simulation with the SULD model;
5. Scenario simulation results processing, evaluation, interpretation and presentation.

1.3. Outline

The present study is divided in seven sections whose main objectives will be described. In the following section, a literature review is presented based on an extensive research regarding the main topics addressed in the present study, that is urban sprawl, economic incentive instruments to steer urban sprawl and models to assess economic incentive instruments that aim to steer urban sprawl. Section 3 corresponds to the case study description of Aveiro, the city that will be studied, including bio-physical and socio-economic characteristics as well as instruments used with the objective to constrain urban sprawl. Next, the methods will be presented, containing some theoretical background, as well as the description and adaptation of SULD, the model that will be used, the different economic incentive instruments application and the data used in the model. In Section 5, simulation results are introduced, including the base scenario description for the city of Aveiro and the different outcomes for each economic incentive instrument simulated, property tax, land tax and transport subsidy. Section 6 represents the discussion, analysing and comparing the obtained results with the literature available to date. Finally, the last Section reports the conclusions withdrawn from the study in question as well as some future recommendations.

2. Literature review

Chapter 2 provides a review on the issue and impacts of urban sprawl (Section 2.1), the economic incentive instruments used to steer and contain urban sprawl (Section 2.2) and, finally, the modelling approaches used to assess the effectiveness of such economic incentive instruments.

2.1. Urban sprawl

It is unquestionably relevant to characterize in a complete manner urban sprawl to comprehend the drivers and consequences of the urbanization process, which can be complex due to its association with thoughtless planning and economic activities (Ji *et al.*, 2006). This is particularly worrisome in Europe's coastal areas that are suffering natural land conversion at a growing pace (EEA, 2006a). Most studies that assess urban sprawl focus on large cities, however this is also a common phenomenon in small and medium sized cities (Carvalho and Pais, 2010).

Even though urban sprawl is originally a United States phenomenon, after the second part of the twentieth century it has been increasingly accepted as a European issue as well. Hence the necessity to "develop more information to better understand what is happening with built up areas and city planning in Europe, and to establish some thresholds and other planning tools to avoid uncontrolled sprawl" (EEA, 2006a, p.8) (Couch and Karecha, 2006; Morollón *et al.,* 2016). By the 1970s, urban sprawl was considered damaging for inner cities and, thus, there was a need for strict control, even though provision of land for construction continued (Couch and Karecha, 2006). As the negative impacts of urban sprawl outweigh the positive impacts, particular attention has been given to constraining urban sprawl – constituting a major challenge for planners (Couch and Karecha, 2006; Ortuño-Padilla and Fernández-Aracil, 2013).

Measuring urban sprawl is, however, difficult and, therefore, so it is to reach a consensus about the policies to adopt to curb or steer this process. Using absolute indicator techniques imply a threshold between a sprawled and a compact city, whereas relative indicator techniques consider different attributes of urban growth that allow for features comparison between cities and even within a city. In short, urban sprawl causes are the ones that influence aspects such as concentration, density, centrality, continuity, proximity and mixed uses, which are helpful to measure this phenomenon despite no standardized method exists (Bhatta *et al.*, 2010; Tscharaktschiew and Hirte, 2011). Nevertheless, it is clear that this phenomenon includes several dimensions and, hence, multiple variables are needed to assess it (Sutton, 2003).

In coastal areas, integrated management is an important subject since the 1990s – aiming for a long-term view and considering, simultaneously, both resources protection and coastal economies promotion because these areas are continuously threatened by artificialization (61% of European coastal build-up land is dedicated to housing, recreation and services). This can be explained by the fact that priority is given to short-term economic concerns (particularly tourism-related) and subsequent urban expansion at the cost of jeopardising, possibly in an irreversible way, all the other existing services that are fundamental to assure the functioning of these coastal systems. Thus, urban sprawl was also unequivocally induced on account of governance inefficiency (EEA, 2006a; Milan and Creutzig, 2016).

Environmental amenities, traditionally located outside the city centres, are considered a keynote feature that influence, to a large extent, households' location preferences (Brueckner *et al.,* 1999). Furthermore, according to Brueckner and Kim (2003), Cavailhès *et al*. (2009) and Wu (2006), an increase in household income will encourage households to move to the suburbs – allowing for the purchase of lager houses near such environmental amenities. Considering that city boundaries are determined by the condition where land rent is equal to the agricultural rent, infrastructure developments will encourage urban sprawl. Closer to city centre land prices are higher and so are housing prices (leading to smaller housing), whereas moving further from central zones land prices are lower and so are housing prices (allowing for bigger housing, despite the larger commuting costs). In addition, suburbs are associated with single or semi-detached houses that represent smaller construction densities compared to apartment buildings with higher densities in city cores. Hence, the increase of housing units or commercial constructions constitutes a sprawl indicator (Bhatta *et al.*, 2010; EEA, 2006a; Tanguay and Gingras, 2011). This explains why urban sprawl is more consistent in high income areas and increases with higher GDP per capita and, alternatively, poorer cities have higher densities (Ortuño-Padilla and Fernández-Aracil, 2013; Wu, 2006). Thus, the decrease in housing, land and transport costs as well as their incorrect pricing are considered the main drivers of urban sprawl (Milan and Creutzig, 2016; Kulmer *et al.,* 2014; Sexton *et al*., 2012; Wu, 2001, 2006).

The technological development associated with private automobiles and transport infrastructure development decreased successively commuting costs, allowing city expansion without rising households' costs. Consequently, travels made are less time consuming and more comfortable (Ortuño-Padilla and Fernández-Aracil, 2013; Nechyba and Walsh, 2004; Tanguay and Gingras, 2011). Accordingly, private car owning is also promoted by income raise since it is a preferable means of transport, encouraging urban sprawl (Bresson, *et al.*, 2003). In addition, the perceived cost of commuting is inferior than the actual social cost, leading to too long commuting encouraging sprawl as commuters do not actual pay for the full cost of their travel (Brueckner, 2003; Su and DeSalvo, 2008).

Urban sprawl and land use changes have been analysed extensively, despite most urban sprawl-related studies regard to the existence and variation in environmental amenities, showing that households' preferences and willingness to pay for depend in a great extent on the specific characteristics of the places (Roebeling *et al.,* 2017; Wu, 2006; Wu and Platinga, 2003). Therefore, most models found in literature that considerate urban sprawl include mostly the impact of green and blue spaces in city compactness, as in Roebeling *et al.* (2007a, 2014b, 2017) and Wu (2006). Despite most of the analysis being statistical, some of the assessments found include simulation approaches, as in Silva (2016) and Roebeling *et al.* (2007a, 2014b). Furthermore, the lack of studies that assess urban sprawl, land use management and its associated importance feed the need to more detailed research (Prates and Melo, 2009).

Summarizing, more scattered or more compact development arises depending on travel costs, land rent costs, household income, housing costs and environmental features of the place, in a way that the specific characteristics of the studied area matter when it comes to policy-making decisions (Schindler and Caruso, 2014; Tanguay and Gingras, 2011; Wu, 2006). The statement that urban sprawl needs to be steered relies on the assumption that the current development rate is too high, and so are travel distance/time, traffic congestion and land conversion, and thus demanding actions against urban sprawl-generated features (Brueckner and Kim, 2003).

2.2. Instruments to steer urban sprawl

Several policy instruments have been used to curb or steer urban sprawl, due to the arising awareness of its negative consequences and increasing trend, in a way that policies need to be enough to counter-balance the economic pressures (EEA, 2016). To better understand the connections between policies and the containment of urban sprawl, attention has been increasingly given to specific instruments to achieve compactness. In fact, since the late 1990s that the European Union has guidelines aiming to encourage more compact cities and to protect agricultural land. Institutional approaches entail the legal framework, that can impose restrictions, make classifications or recommendations, as well as specifying liability and, hence, provide the base and rules from which decisions and actions are taken, such as land use restrictions (Abrantes *et al.*, 2016; Perman *et al.,* 2003). Command and control instruments are based on rules, regulations, obligations and restrictions and, thus, imposing or limiting certain types of behaviour, quantities or qualities (Perman *et al.,* 2003). Although being the most used instruments to curb or steer urban sprawl, command and control instruments have been criticised for being too strict, to contribute to the stagnation of construction, for not considering externalities, and for its limited use and effectiveness in dealing with urban sprawl (Altes, 2008; Couch and Karecha, 2006; Litman, 1997; Perman *et al.,* 2003; Prates and Melo, 2009). Finally, economic incentive instruments are designed to encourage and promote more sustainable behaviours (Perman *et al.,* 2003). After the economic crisis, environmental subsidies and taxes have been gaining weight in Europe assuming that they might be easier and more effective than command and control instruments (EC, 2016; EEA, 2010). In fact, according to EEA (2013b), there is a potential revenue increase related to environmental taxes of €2.2 billion for Portugal.

Economic incentive instruments provide a tool to curb or steer urban sprawl by, simply, considering urban sprawl as an economic issue. I.e., unmeasured construction only exists due to the failure of taking into account externalities – implying that development will occur sooner than what is considered social optimality. Hence, pricing reforms are needed to correct this market failure arising from not internalizing the full costs associated with, for example, noise, congestion and pollution (Altes, 2009; Brueckner and Kim, 2003; Jou and Lee, 2007). Positive (subsidies) or negative (taxes) incentives can be used to correct this gap (Perman *et al.,* 2003). Various economic incentive instruments can be considered for controlling urban sprawl, including property taxes, land taxes and public transport subsidies.

Property taxes have been pointed-out as an effective instrument to control urban sprawl (EEA, 2006a; Eurostat, 2014) and for being less detrimental to economic growth (EC, 2012). Housing cost is considered a key factor influencing urban sprawl, being the under-pricing of housing a driver of less compact cities (Couch and Karecha, 2006; Milan and Creutzig, 2016). This is because lower housing prices may result in households being able to afford larger commuting distances and bigger houses in the suburbs near environmental amenities (EC, 2016; Ortuño-Padilla and Fernández-Aracil, 2013). Furthermore, the higher prices in city centre' houses might also contribute to forcing households to move outwards, where usually more affordable or best conditions in housing can be found with larger living spaces (Sutton, 2003). Thus, higher housing costs associated with a property tax leads to smaller dwelling sizes as these costs are passed onto households that will have to pay more, thus reducing living space and improving city compactness (Brueckner and Kim, 2003). Hence, most authors unveiled that property taxes are efficient in steering urban sprawl and controlling land conversion as smaller living spaces are promoted and development is delayed (Bento *et al.* 2005; Brueckner, 2001; EC, 2012; Groves, 2009; Jou and Lee, 2007; Milan and Creutzig, 2016; and Song and Zenou, 2006) and pose a driving force for household location (Kulmer *et al.,* 2014). Most property-related taxes are recurrent, which means that they are paid annually based on some measurement of the property value (other less used types include transactions and transfers taxes) (EC, 2016).

Land taxes are acknowledged to delay land development (Banzhaf and Lavery, 2010; Cho *et al*., 2009; EC, 2012; Institute for Fiscal Studies, 2011; Jou and Lee, 2007; Milan and Creutzig, 2016; and Wu, 2001) and, moreover, to address the failure in internalizing costs associated with land conversion (Altes, 2008). The potential success of this instrument can be related to the fact that land use conversion becomes more expensive and, thus, property costs increase (Altes, 2008; Wu, 2001) and, as a consequence, there is a trend to make land use more intensive and decrease land use per capita (Sutton, 2003). This economic incentive instrument is important because land costs are considered too low (Abrantes *et al*., 2016; Almeida *et al.,* 2013). However, it is quite difficult to value land accurately and development might continue if the benefits from land development surpass the opportunity costs of land (EEA, 2010; Institute for Fiscal Studies, 2011).

There is, however, some controversy related to property and land taxes. Despite being considered as non-distortive by the Institute for Fiscal Studies (2011) and EEA (2010), as their supply is not very responsive to their prices, some authors did not find any significant correlation between property taxes and urban sprawl (Banzhaf and Lavery, 2010; Milan *et al*., 2016) while other authors unveiled that the effects of a property tax can be ambiguous (i.e. encouraging urban sprawl if dwelling size if fixed or steer it if dwelling size is not fixed; Brueckner and Kim, 2003). In fact, according to Peng and Wang (2009), the optimal tax scheme is to trade the property tax for a land tax – hence maximizing welfare and leading to a smaller city.

As growing car ownership is a major driver of urban sprawl, some measures must be taken in order to reduce its use and to achieve a more efficient city transport system, which is essential for economic competitiveness and improved quality of life for the households (EEA, 2013a; Poelmans and Rompaey, 2009). Furthermore, private car use is responsible for externalities, congestion, increased fuel consumption and emissions, which could justify taxation in this sector, internalizing all costs (Bresson, *et al.*, 2003; Tscharaktschiew and Hirte, 2011). The most straightforward measure would be to increase fuel costs to discourage private car use. In fact, according to Bureau (2012), Creutzig (2014), Molloy and Shan (2010), Potter *et al*. (2006), Rodriguez (2013), Song and Zenou (2006), Tanguay and Gingras (2011) and Wu (2001, 2006), fuel taxes can be an efficient tool to control urban sprawl. Fuel taxes also consider the external costs (such as infrastructure, maintenance and environmental) and, for that reason, charges and taxes can be seen as the most effective instruments to promote more efficient transport systems and to control urban sprawl (Potter *et al*., 2006; Tanguay and Gingras, 2011). Other commonly applied taxes in the transportation sector are associated with vehicle purchase, use and ownership. However, these taxes cannot be too low, otherwise it would put at stake its effectiveness, so for fuel taxes to be effective, higher values must be charged (Potter *et al*., 2006).

Fuel taxes are, however, already the most applied measure in the transport sector (77% of environmental taxes are energy related, within which more than three quarters are represented by fuel taxes; EC, 2016) and, nevertheless, the urban sprawl trend is still rising. In addition, high fuel costs might be socially stressful and promote social inequalities (Dodson and Sipe, 2007; Molloy and Shan, 2010). Moreover, Tanguay and Gingras (2011) found no significant correlation between fuel taxes and urban sprawl and Kulmer *et al.* (2014) findings report that transport costs do not affect significantly households' location. Besides this, and Potter *et al*. (2006) and Litman (1997) both hypothesized that to make an impact, fuel prices must be much higher than they are, as they only constitute part of the total user costs. Besides this, Rodriguez (2013) unveiled that households might not resettle on behalf of fuel price alterations unless they already had the desire to move. For these reasons and, since private car is competing directly with public transport use, other directions must be found, maybe through a public transport subsidy which could give a boost to urban compactness, as proposed by Dodson and Sipe (2007) and Molloy and Shan (2010). This cross-elasticity between car and public transport could be a way to try-out new perspectives to control urban sprawl (Bresson, *et al.*, 2003).

In fact, public transportation is already subsidized in various countries and it has shown to be welfare enhancing and to increase consumer surplus (Tscharaktschiew and Hirte, 2011). Some studies show that public transport is overpriced and its use can help to develop more compact cities, promoting the densification of the inner suburbs (Kulmer *et al.*, 2014; Molloy and Shan, 2010; OECD, 2002; Rodriguez, 2013; Su and DeSalvo, 2008). According to Bresson, *et al.* (2003) and Kulmer *et al.* (2014), the use of public transport should be increased as it would discourage the use of private car – a well-established driver of urban sprawl but also a consequence of this scattered development. Moreover, for lower income households public transport is essential concerning their housing location choices, while higher income households use predominantly private car (Altes, 2008; Brueckner, 2003; EEA, 2010). Another important issue is that public transport use is dependent on volume and price – i.e. the use of public transport is encouraged in high congestion areas while public transport is more viable in compact cities (Bresson, *et al.*, 2003; Creutzig, 2014; Dodson and Sipe, 2007; EC, 2011; Su and DeSalvo, 2008; Wang *et al.*, 2015). Although little attention has been paid to the use of this economic incentive instrument as a tool to control urban sprawl (Tscharaktschiew and Hirte, 2011), the improvement of public transportation is considered necessary to curb and steer urban sprawl (Ambarwati *et al.*, 2014; Su and DeSalvo, 2008; Tanguay and Gingras, 2011). Public transport subsidization also constitutes an attempt to put an end to harmful subsidies to road infrastructure or travel costs, that reduce welfare by increasing congestion and urban sprawl. Indeed, the volume of subsidies in Europe in 2005 was about 270 billion €, within almost half of the value was available to road infrastructure encouragement (Tscharaktschiew and Hirte, 2011). Portugal as well as other European countries received assistance from the EU Structural and Cohesion funds to improve its coastal infrastructure, which has proven to increase sprawl (EEA, 2006a). In response to that, subsidies provided must be thoroughly thought and more favourable to public transport than to private car use (EEA, 2015). In fact, Tscharaktschiew and Hirte (2011), showed that all subsidies contribute to suburbanization, even if small, apart from public transport subsidies, that also reduces congestion costs.

Besides this, public transport subsidies have an environmental positive effect since its use decreases greenhouse gases, by promoting more green transportation, which is not true when fossil fuels are subsidized. The challenge is to reduce oil dependence in the transportation sector, without compromising its operation and population mobility. For that, new transport patterns must emerge, since urban transport is responsible for about a quarter of total CO_2 emissions, being imperative to encourage cleaner modes such as public transport. In response to that, new measures must be found, which obviously implies costs and it is not an easy planning. Transport charges and taxes must be restructured to include all external costs, to eliminate tax distortions and harmful subsidies (EC, 2011; EEA, 2015;

OECD, 2002). There is a concern that just one instrument might not achieve the desired outcomes, so more studies are needed about transport policies (Potter *et al.*, 2006).

Summing up, property and land taxes as well as public transport subsidies play an important role in spatial location patterns as they affect households' willingness-to-pay for housing further away from or closer by the city centre – meaning that they are considered an important answer to curb or steer urban sprawl (Altes, 2008; Tscharaktschiew and Hirte, 2011). Economic changes in property, land and transport costs seem to have an important impact on urban sprawl, as its reduction may be linked to urban fringe expansion (Altes, 2008; Cavailhès *et al.*, 2009; Peng and Wang, 2009). Moreover, revenues from environmental taxes can be used to shift taxation from labour and to reduce harmful subsidies, thus maximizing economic growth, by readdressing tax systems (Ministério do Ambiente, Ordenamento do Território e Energia, 2014). Based on the existing literature on economic incentive instruments that aim to curb and steer urban sprawl, it can be concluded that property taxes, land taxes and public transport subsidies are suitable candidate instruments to contribute to a more compact city model. Despite the lack of information on efficient tax design, changes in property costs, land prices and public transport costs all have shown evidences to pose an impact on urban development patterns (Milan *et al.*, 2016; Ortuño-Padilla and Fernández-Aracil, 2013).

2.3. Models to assess economic incentive instruments that aim to steer urban sprawl

A model can be defined as an abstract representation of an object, phenomena or reality, allowing an increased knowledge about the context in question through experimentation and that are useful to analyse and simulate urban patterns (Pinto, 2008; Pinto *et al.*, 2009). This has led to the increase in the available models, displaying its relevance, in a way that "land use modelling, especially if done in a spatially-explicit, integrated and multi-scale manner, is an important technique for the projection of alternative pathways into the future" (Veldkamp and Lambin, 2001, p.1), as it helps to establish land use change drivers to create future scenarios and to assess associated impacts (Haase and Schwarz, 2009). Economic models usually represent small scale processes and rely on the decision-maker choice so as to maximize their utility, profit or income, which allows perceiving their response to different policies and enabling the evaluation of economic incentive instruments (Roebeling *et al.,* 2014a, 2017). Within the economic models, a division can be made between spatially and non-spatially explicit approaches. The latter assume a featureless plane and, thus, have been criticized for not considering heterogeneous landscape characteristics (Roebeling *et al.,* 2014a, 2017; Wu, 2006). This has led to the occurrence of spatially explicit models that are based on the individuals' willingness to pay for goods and services, albeit most of them applied to hypothetical situations (as in Haase and Schwarz, 2009; Schlapfer *et al.,* 2015; Wu, 2001; Wu and Platinga 2003).

Hence, for the realization of this study, some economic models have been analysed, including:

- Statistical models assess instruments that aim to promote sustainable urban development, based on observed data relating urban sprawl and economic incentive instruments to urban development patterns. These models require large amounts of observed data, which is not always available (Roebeling *et al.,* 2017). This is the most common way of evaluating the effectiveness of different instruments, as they are easier to implement and relevant to test theoretical implications – despite of only allowing the appraisal of actually implemented measures and pose restrictions to extrapolations (Altes, 2008; Irwin *et al*., 2009; Lambin *et al*., 2000; Veldkamp and Lambin, 2001). Almeida *et al*. (2013), Brueckner (2001), Groves (2009), Institute for Fiscal Studies (2011), Milan and Creutzig (2016) and Song and Zenou (2006) evaluate the impact and effectiveness of property taxes on the containment of urban sprawl; Altes (2008), Banzhaf and Lavery (2010), Cho *et al*. (2009), Institute for Fiscal Studies (2011), Milan and Creutzig (2016) and Tanguay and Gingras (2011) apply statistical models to assess the impact of land-related taxes on cities development patterns; and, finally, Banzhaf and Lavery (2010) and Su and DeSalvo (2008) assess the outcomes of transport-related taxes on urban development patterns. Overall conclusions of these studies indicate that the application of property taxes, land taxes and transport taxes can, if well-planned, effectively constrain urban sprawl.
- Simulation models assess instruments that aim to promote sustainable urban development do not require the same amount of past observed data, as they can predict the outcome of not yet implemented measures – allowing ex-ante assessment and visualization of planning policies and to study land conversion (Pinto *et al*., 2009). In fact, according to Lambin *et al*. (2000) and Poelmans and Rompaey (2009), these models are particularly suitable for predicting land use changes and to explore different policies. Hence, they can be used to provide insights in the most effective policies within the suite of existing alternatives, in order to achieve the most sustainable option. Bento

et al. (2005), Jou and Lee (2007), Kulmer *et al.* (2014) assessed the impact of property taxes on urban density patterns, while Jou and Lee (2007) and Wu (2001) assessed the impact of land taxes on urban density patterns. Brueckner and Kim (2003) and Peng and Wang (2009) explore the impact of property and land taxes on urban sprawl. Ambarwati *et al*. (2014) and Tscharaktschiew and Hirte (2011) evaluate transport policies and the impact of improving the public transport network on a city's development (despite no simulation study was found that assesses only public transport and sprawl). In contrast, most simulation approaches, such as the ones included in Brueckner *et al*. (1999), Cavailhès *et al*. (2010) and Wu (2001, 2006), encompass household settlement patterns related to urban amenities and preferences. Overall conclusions of these studies include: i) property taxes are efficient anti-sprawl policies; ii) under some circumstances property taxes can either encourage or contain urban sprawl, whereas land taxes are less distortionary; iii) land taxes positively influence sprawl patterns; iv) encouraging the use of public transport is welfare enhancing without contributing to a more scattered development; and v) land use patterns and household settlement preferences depend on the spatial distribution of amenities in a city. Nevertheless, mostly non-European cities were used besides the monocentric-cities models, assumptions on income (undifferentiated) were often made and simplifications about amenities were considered, as well as the lack of including the supply side in some. For these reasons, real applicability is limited as most studies are based on abstract situations (Irwin *et al.,* 2010; Roebeling *et al.,* 2017; Saraiva *et al.*, 2016). Only Bento *et al.* (2005) tested the impact of property, land and transport taxes, despite only assessing fuel taxes and using a theoretical simulation modelling approach.

Numerous studies use spatial models to explain urban landscape features, only few studies relate to urban sprawl, and even fewer studies assess economic incentive instruments as a tool to curb or steer this uncontrolled development (Cotteller and Peerlings, 2011; Wu, 2006). Also, there are few studies that assess economic incentive instruments using simulation models – i.e. these are mostly applied to assess the impact of amenities, transport infrastructure and population dynamics on urban development patterns (e.g. Roebeling *et al.,* 2014a, 2014b; Wu and Platinga, 2003; Veldkamp and Lambin, 2001). In fact, although some of these features have already been analysed, they have never been considered simultaneously with a (spatially-explicit) simulation approach while, in addition, variations within the assessed economic inventive instruments are scarce. Given the pressure that natural areas are suffering, however, simulation models are crucial to provide decision makers with justified information on their options concerning land use planning

(Pinto, 2008; Pinto *et al*., 2009). Likewise, the EU and other policies feed the need for the ex-ante assessment of proposed economic incentive instruments that aim to enhance urban sustainability and control urban sprawl – ensuring that the value-added of proposed policies is demonstrated.

3. Case study description

A case study is provided for the City of Aveiro, a medium-size city on the northwest coast of Portugal. This coastal area experienced one of the biggest increases in artificial areas in Europe between 1990 and 2000 (EEA, 2006a). The natural areas encourage residential settlements, which has been pointed out by Alves (2014) as a major driver of disperse development and subsequent pressure on these ecosystems. Thus, the urbanization pattern in this area is mainly diffuse, with urban uses detached from the city centres and, thus, the line between urban and rural is quite unclear. The desire for holiday houses from Portuguese and non-Portuguese households also greatly contributes to the exacerbation of this phenomenon (Alves, 2014; Pinto, 2008). Coastal population growth and agricultural land conversion (due to the lower prices in surrounding areas) between 1990 and 2000 in Portugal, was one of the highest at a European level – Portugal being one of the countries that experienced the “highest trends in growth of artificial surfaces and sprawling in the whole coastal zone” (EEA, 2006a, p. 20) (with an increase over 50% of scatter residential in the same period) (EEA, 2006a).

The most notorious cases of urban expansion are related, either, to increased population density, or, to significant economic growth. Hence, conversion rates of natural land can be higher than population increases, especially in coastal areas. There is a growing trend in which expansion is happening not only in larger cities but also around small and medium-sized cities in coastal areas (EEA, 2006a). For the Aveiro region, Pinto (2008) and Pinto *et al*. (2009) showed that urban expansion is expected to increase significantly by 2030. In fact, according to CCDRC (2011), one of the greatest environmental concerns is related to the increase in scattered occupation of this coastal area. The severe shortcomings concerning land use planning in Portugal are one of the problems associated with land conversion (Cunha and Melo, 2007).

3.1. Bio-physical

Location

The Aveiro coastline extends for 65 Km and has a total area of 1 690 Km^2 (Pinto, 2008; Pinto *et al*., 2009; UA, 2014). It comprises nineteen districts, including Águeda, Albergaria-a-Velha, Anadia, Arouca, Aveiro, Castelo de Paiva, Espinho, Estarreja, Ílhavo, Mealhada, Murtosa, Oliveira de Azeméis, Oliveira do Bairro, Ovar, Santa Maria da Feira, São João da Madeira, Sever do Vouga, Vagos and Vale de Cambra (Saraiva *et al.*, 2016; Silva, 2016; see Fig.3). The main urban centre is the City of Aveiro that hosts most services, mobility infrastructures and industrial activities; secondary centres include Ílhavo, Estarreja, Albergaria-a-Velha, Oliveira do Bairro and Ovar (Altes, 2008; CCDRC, 2011; for a detailed review on each district, see UA, 2014).

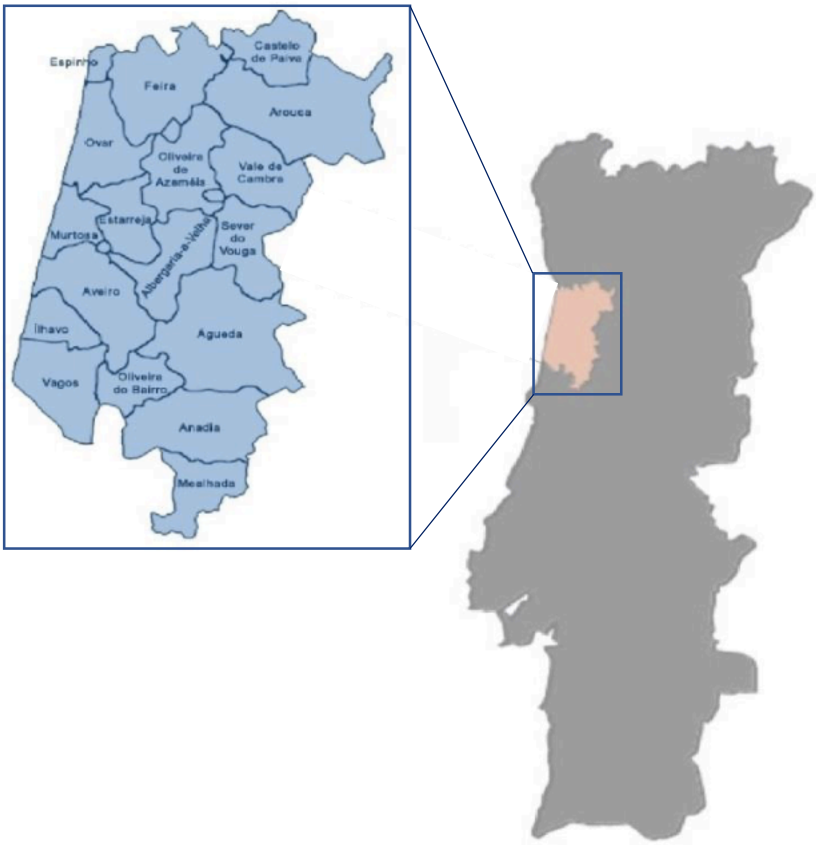


Fig.3. Location of the Aveiro Region in Central Portugal (adapted from Silva, 2016).

Environment

Environmentally speaking, the Aveiro region comprises areas with great ecological value that are endangered due to high levels of pollution, namely air and water pollution from, in particular, industrial origin (CCDRC, 2011). There are several important natural areas: São Jacinto dunes national reserve (protected by the national network of protected areas, Law nº 41/79 of 6th March), SPE (Special Protection Areas) of Ria de Aveiro Lagoon, Barrinha of Esmoriz, Pateira de Fermentelos, Mira, Gândara and Gafanha dunes, and the Vouga river (UA, 2014). The Vouga river and catchment represent the main water course, with several wetlands and lagoons – such as Barrinha of Esmoriz, Barrinha of Mira and Ria de Aveiro Lagoon (Pinto, 2008).

Risks

The Aveiro region presents high natural risks, such as from fire and coastal erosion. In addition, the area suffers from water and air pollution associated with industries in the region – jeopardizing protected places, water bodies and air quality. Moreover, as it is a plane region with low altitude it is susceptible to floods. All this is accompanied by the urban sprawl phenomena with urban fragmented expansion towards the suburbs with a mix of land uses – resulting in landscape losses, infrastructure development, ecosystem losses and degradation of historical centres (DGT, 2007b; Pinto, 2008; UA, 2014).

Land use

The Aveiro region is under threat due to the intensive land use, especially the artificial ones. The increase of artificial land dates to the 60s, with labour migration towards coastal cities where industries were located (Pinto, 2008). There was a massive increase in urban land uses between 1975 and 1990 (over +300%), when scattered development became more visible. Since that period urban growth has slowed down, with 9% growth-rates between 1990 and 2006. This means that, in 1975, the predominant land use around the Ria de Aveiro lagoon was natural (agricultural and forest), where artificial surfaces only occupied 5%; by 2006 artificial surfaces occupied up to 13% (Roebeling *et al.,* 2011). Looking towards the future, it is predicted by Pinto *et al*. (2009) that 28% of the coastal area of Aveiro will be urban land by 2030 (corresponding to a 79% increase between 1990 and 2006 and an expected 68% increase between 2006 and 2030). The same values are reiterated by Pinto (2008), even adding that constructed areas increased at a five times higher rate than population increase and preconized an increase by 196% between 1990 and 2030. Scattered of this coastal area is considered one of the greatest environmental concerns in the Aveiro region (CCDRC, 2011).

The urban sprawl phenomenon is mostly visible along the coastline, in the North around Estarreja and Murtosa, in the Southeast between Vagos and Mira, and in the East between Albergaria and Mealhada (CCDRC, 2011; DGT, 2007b). Urban patterns in rural areas are mainly one family per house without high buildings; in coastal areas the 'second house' phenomenon is more visible with, typically, seasonal use (UA, 2014). Anadia, Aveiro, Albergaria-a-Velha and Sever do Vouga are the districts that mostly need housing renovation (UA, 2014). Thus, the region is known for having a dispersed artificialization patterns (see Fig.4), namely in the North and South. The City of Aveiro has a more polycentric urban structure, with a mix of uses (Alves, 2014; Carvalho and Pais, 2010; CCDRC, 2011).

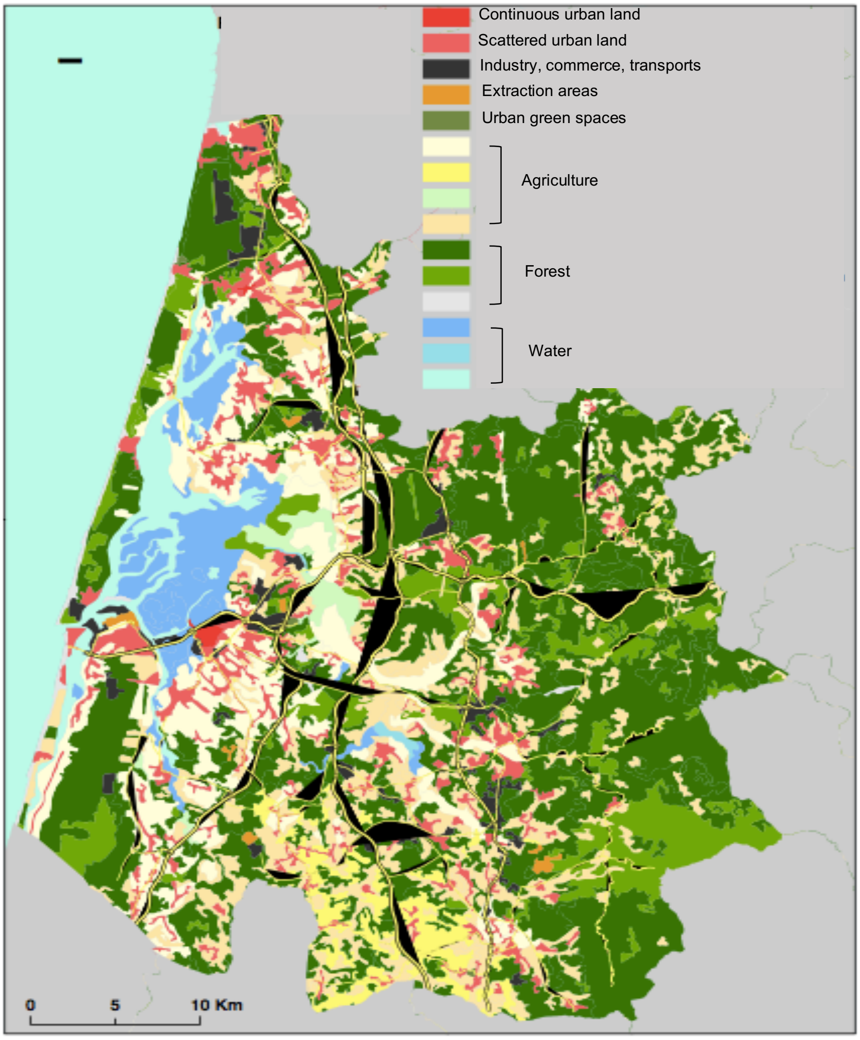


Fig. 4. Land use in the Aveiro region in 2006 (adapted from UA, 2014).

Summing up, the Aveiro region is strongly occupied with infrastructures and scattered urban development, with the Ria de Aveiro lagoon as a receptor of pollution produced within the region – setting forth as the greatest conflict concerning this region planning (CCDRC, 2011). According to DGT (2007a), the Aveiro region is characterized by abandoned/destroyed forests, disorganized agricultural areas, urban-industrial occupation *chaos* and environmental problems related to industrial areas.

3.2. Socio-economic

The Aveiro region is considered one of the competitive drivers of Portugal with several industrial centres, such as Ílhavo, Águeda, Albergaria, Vagos and Oliveira do Bairro (Alves, 2014; DGT, 2007a). Besides this, Aveiro poses significant importance on knowledge services (university; research centres) as well as administrative, social and commercial functions. Its great industrial component is deeply related to the Porto metropolitan area, important connections are made through the Aveiro port and the region hosts an important tourism sector (CCDRC, 2011; EEA, 2006a).

Infrastructure

Concerning accessibility, the Aveiro region has a favourable position, as it is connected by four major highways (connecting the city nationally and internationally; IC1/A17, IP1/A1, IC2 and IP5/A25), one provincial road (N109) and an intercity railway station (Alves, 2014; CCDRC, 2011). The Aveiro region constitutes an important link between Lisbon and Porto, with more important transport infrastructures and more scattered population existent around more considerable urban agglomerations (such as Aveiro, Ovar, Ílhavo and Águeda). Public transport in the Aveiro region as well as the City of Aveiro is still scarce in some areas (CCDRC, 2011; Fig.5), thereby noting that public transport in the City of Aveiro is mainly provided by a single operator. Private car use in the city is estimated at just over 0.5 million trips per day (CIM Região de Aveiro, 2014).

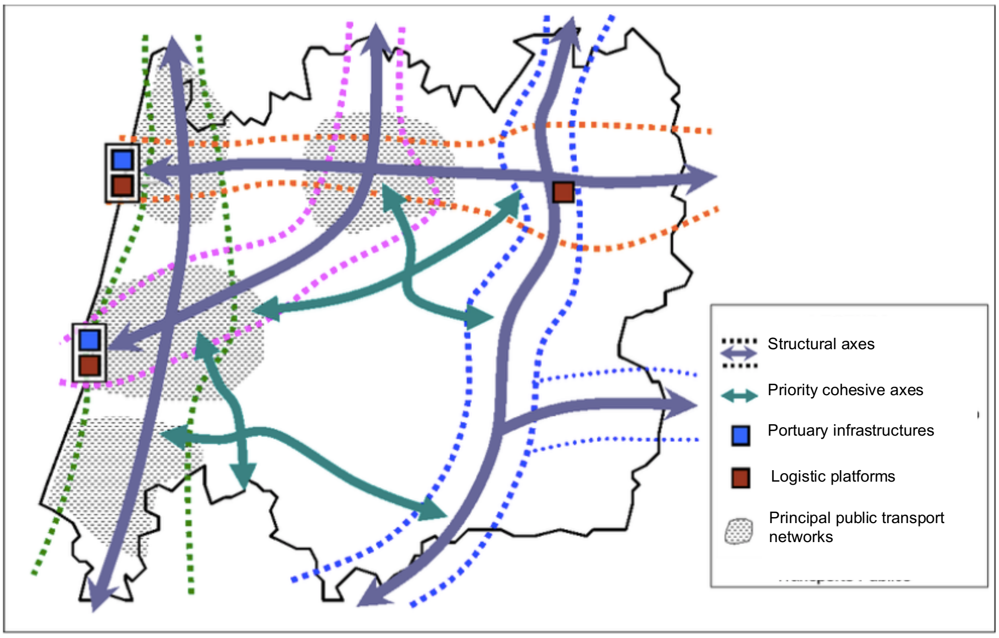


Fig. 5. Accessibility and transportation systems in Centre Region (Portugal) (adapted from CCDRC, 2011).

The commuting trips are mainly done by individual vehicle (76%), followed by walking (20%) and public transport (13%; CCDRC, 2008). The train also has a significant demand, connecting the City of Aveiro with the rest of the country, presenting annual growths of around 4.3% (CIM Região de Aveiro, 2014). It is acknowledged that the public transport offer is inefficient in areas with less population density – i.e. offer is only considered sufficient in Aveiro, Ílhavo and Murtosa. It is estimated that 2% of the population has no access to public transportation, increasing to 7% (nearly 25 000 inhabitants) during school holidays. In addition, frequency of offer is severely affected during school holidays – 18% of the population has less than six daily circulations available. For that reason, a more balanced public transport supply should be attained to avoid social exclusion (CIM Região de Aveiro, 2013; see Fig.6).

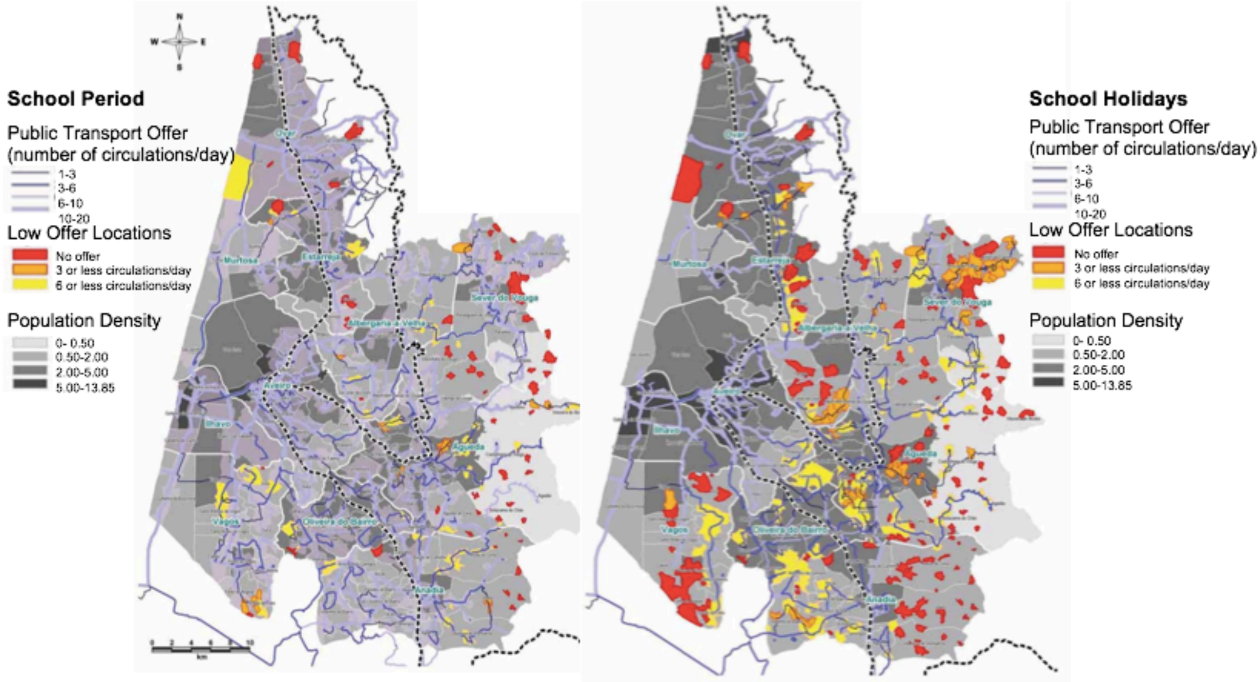


Fig.6. Public transport offer in Aveiro Region – low offer areas and associated population density in school period and school holidays (adapted from CIM Região de Aveiro, 2014).

One of the problems associated with commuting is the high external cost. These include traffic, accidents, environmental emissions and noise, that in Aveiro amount up to 139 million euros per year (about 19% of all mobility costs; Table 2; CIM Região de Aveiro, 2014). It is estimated that 21% of the private car costs are external, whereas the external costs of public transport are estimated at 13% (CIM Região de Aveiro, 2014).

Table 2. External costs in Aveiro Region associated with transport in 2010 (adapted from CIM Região de Aveiro, 2014)

Total external costs	Costs (million €)
Accidents	63.839
Noise	8.590
Local pollutants	8.710
GHG	11.725
Traffic congestion (time)	46.411
TOTAL	139.276

Population

The Aveiro region has a total population of approximately 364 300 inhabitants, which can be translated to around 215.2 inhabitants/Km^2 (INE, 2015). Most of the population is settled in Aveiro and Ílhavo, followed by Águeda and Ovar. The number of inhabitants in the Aveiro region grew from 191 242 in 1991 to 218 189 in 2006 (+14%), well above the 5,6% increase for central Portugal over the same period (Pinto *et al.,* 2009). This shows an increasing population trend that, however, recently has been stabilizing and, in some, areas, even has been declining. According to INE (2012), a 10% decrease in population is expected for 2030, related to ageing population, declining fertility rates and increasing emigration (due to the economic crisis). This recent trend may not, however, result in a reduction in urban sprawl as the build-up area may still increase (Alves, 2014; Bhatta *et al.*, 2010; Saraiva *et al.*, 2016). The Aveiro region is then known for its scattered patterns, trend that is less worrisome in Aveiro, Ílhavo and Ovar, although 83% of the region has less than 500 inhabitants (Fig.7) (CIM Região de Aveiro, 2014).

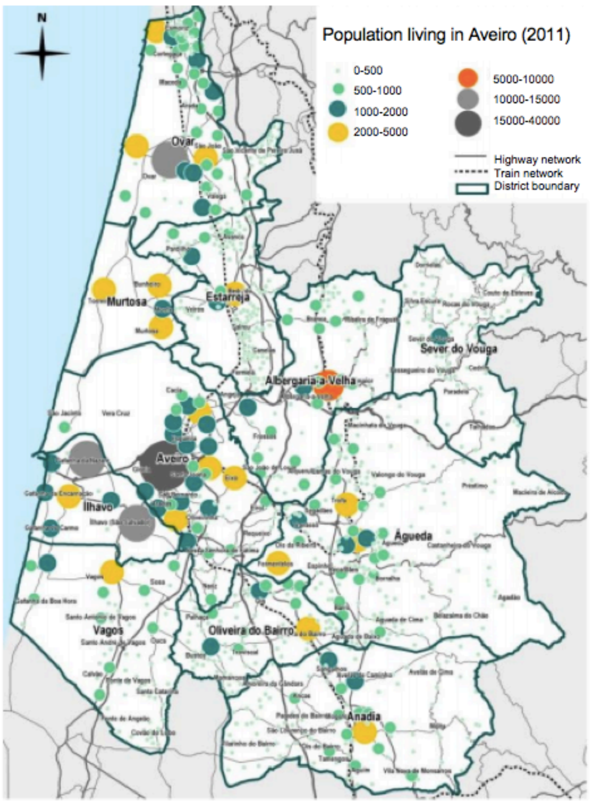


Fig.7. Population of Aveiro Region per localization in 2011 (adapted from CIM Região de Aveiro, 2014).

Economy

Industrial land uses, namely industry, commerce and general infrastructure reinforcement, followed the same increasing trend as the other artificial land uses – showing a growth of 154% between 1990 (800 ha) and 2006 (1900 ha) (Alves, 2014). In the Aveiro region, the 1990s were characterized by a significant increase in agricultural land purchase by non-farmers due to the significant rural exodus (see Alves, 2014; DGT, 2007a). As a consequence, the city underwent severe urbanization and industrialization over the last decades, especially around the Ria de Aveiro lagoon. In the Aveiro region services dominate the employment sector (such as tourism, education and commerce), followed by extractive (salt mining and fishing activities), transformation (such as chemical, paper, mineral and metallurgy) and construction industries and, to a minor extent, by agriculture and production activities. In fact, the establishments density (number per Km^2) (24.2) is quite higher than the average in Portugal (12.8) and the Central Portugal (9.1) (INE, 2015; UA, 2014).

Besides pure industrial economic value, riparian coastal areas such as the Ria de Aveiro lagoon have, according to Constanza *et al*. (2014), very high value in comparison with other ecosystems. The Ria de Aveiro lagoon is a complex system that creates a unique landscape and provides a wide range of services, such as maritime trade and fishing activities, tourism, sports and other nature-related activities. It is estimated that ecosystem service values in the Ria de Aveiro region decreased from approximately 290 million euros/year in 1975 to 245 million euros/year in 2006, due to land use transformation and coastal erosion (Roebeling *et al.,* 2011).

3.3. Instruments used to steer urban sprawl

Considering the pressure that the Aveiro region is suffering and is expected to suffer, especially in the coastal areas, it is imperative that scenarios and tools to promote a more sustainable urban planning are presented and compliance is promoted (Abrantes *et al.,* 2016; Pinto *et al*., 2009). Furthermore, the city's territory is fragmented at an administrative level, which causes problems concerning land management, so different policies are necessary with an appropriate cooperation and integration of different sectors (Alves, 2014, DGT, 2007a). This section reviews the legislation and planning tools as well as the economic instruments employed in Portugal, in general, and in the Aveiro Region, in particular.

Legislation and planning

The first legislation on soil policy in Portugal was implemented in 1970 (Law No. 576/70 of 24th November), which was necessary due to the rural exodus that began in the 50s and exploded on the 60s – contributing directly to an unplanned increase of urban land use. The attempts to regulate land use continued with the alteration of this law (Law No. 795/76 of 5th November) that foresee urban control and recovery (UA, 2011). Command and control instruments, that include the control of urban sprawl in a more sustained perspective, have been introduced in Portuguese legislation in 1998 following EU guidelines – including binding and guiding policies and programmes (composing the Policy on Territorial Management and Urbanism (Law No. 48/98 of 11th August and revised by Law No. 380/99 of 22nd September, Law No. 310/2003 of 10th December and Law No. 31/2014 of 30th May)) (Abrantes et al., 2016; Prates and Melo, 2009). This includes restriction in areas to construct, namely the ones that are part of EU's network of nature conservation areas (such as the Ria de Aveiro lagoon Natura 2000 area; EEA, 2006a) and national conservation programmes (including the São Jacinto, Mira, Gândara and Gafanha dunes). Moreover, there are several important species and, hence, the area is covered by the Birds (Directive 2009/147/EC) and Habitat (Directive 92/43/EEC) Directives (CCDRC, 2011; Pinto et al., 2009; Silva, 2016). The following policies also pose relevance considering coastal areas management: the National Ecologic Reserve (REN; Law nº 321/83 of 5th July), the Environmental Impact Assessment Directive (85/337/EEC), the Strategic Environmental Assessment Directive (2001/42/EC) and the Seashore Planning Projects (POOC; Law nº 309/83 of 2nd September) (EEA, 2006a; Pinto, 2008).

The broader plan is the national plan (PNPOT- *Programa Nacional da Política de Ordenamento do Território*), whose reference guidelines should be translated into more geographical-specific plans (PROT- *Plano Regional de Ordenamento do Território*), and that aims at the sustainable development of all cities by 2025 (based on Law nº 48/98 of 11th August and approved by Law nº 58/2007 of 4th September) (DGT, 2007a; Pinto, 2008; Quintão *et al.*, 2012). PNPOT underlines the need for measures that prevent urban sprawl, city centre degradation, public policy insufficiency and dependence on private/public transport. Furthermore, PNPOT puts a great deal of effort in landscape maintenance and natural resources protection through articulation with urban features, as to encourage polycentric and cohesive systems while promoting cooperation to accomplish economic growth and social welfare. Finally, PNPOT aims to encourage public transportation development through the integration of economic dimensions – including investments, subsidies and others (DGT, 2007a, 2007b).

For Central Portugal, the PROT-C (*Plano Regional de Ordenamento do Território-Centro*; Law No. 31/2006 of 23rd March) also aims at sustainable development, including land use, occupation and transformation, through an integrated policy perspective with institutional cooperation to promote urban cohesion, polycentric urban features, coastal protection and risk minimization. It is supposed to guide public policies to consider, among others, landscape features, environmental amenities valuation, city centres recovery, infrastructure modernization and public transport conditions, economic and tourism growth, and natural and ecological resources appreciation (CCDRC, 2011; Quintão et al., 2012). However, PROT-C only constitutes a guideline territory management project and, hence, requires further policy application in order to implement real measures. Concerning public transport, the PROT-C preconizes that the development of this sector is imperative, especially in scattered areas, and that densification should be promoted around areas where public transport is efficient. PROT-C acknowledges the urgency in stopping urban sprawl, encouraging the occupation of already urbanized areas and requalifying existing infrastructures (CCDRC, 2011; DGT, 2007a).

PROT-C should then be integrated into the municipal plans (PMOT- *Plano Municipal de Ordenamento do Território*, Law No. 48/98 of 11th August, Law No. 58/2007 of 4th September) that must define and program land uses according to the previous guidelines in more generic plans and should include the definition of non-construction areas. These are regulatory thus function as management instruments. They should be revised as often as significant changes occur, maximum 10 years a part (CCDRC, 2011; DGT 2007a, 2007b). Furthermore, PMOT should be addressed more specifically in territorial action plans PAT (*Programa de Ação Territorial*) that include private and public entities actions and objectives to implement the desired measures (DGT, 2007a).

Economic incentive instruments

Regarding property taxes, the existent include: the IMI (major revenue source, providing 1 035 million euros in 2009, (CENSE/FCT-UNL, 2012)), a Municipal Transaction Tax (IMT), taxes on investments and taxes on construction, maintenance and reinforcement of urban infrastructure (MUT). The IMI is based on several variables that include use, location, quality and use; however, the values are still too low and do not reflect the real prices and overlooks environmental aspects as protected area restrictions (Prates and Melo, 2007, 2009). Property taxes (IMI) in the Aveiro region vary between 0.45% in the city of Aveiro to 0.30% in Águeda, Anadia, Arouca, Castelo de Paiva, Mealhada, Oliveira do Bairro, Vagos and Albergaria-a-Velha (Autoridade Tributária e Aduaneira, 2016a). According to Eurostat (2014), property taxes might be raised in Portugal as, in 2012, its revenues were above the European average (4.3% and 5.7%, respectively), proposing the raise of this tax with an accordingly decrease on other indirect taxes in which Portugal relies. Furthermore, Portugal's government has not been planning to contradict this trend, since it is planned a 50% property tax reduction in buildings that produce renewable energy and rural buildings in areas that provide ecosystem services (currently the fixed levied tax on rural buildings is slightly higher (0.8%) than urban buildings), being already stated by Almeida *et al.* (2013) that the values charged are well below the maintenance costs. In fact, between 2014 and 2016, property tax maximum for urban buildings has decreased by 0.05% (0.3%-0.5% in 2014); (0.3%-0.45% in 2016) (Autoridade Tributária e Aduaneira, 2016a; PwC, 2014, 2015, 2016). Besides this, each district has the freedom to reduce this tax up to 20% (Autoridade Tributária e Aduaneira, 2016a). Although this value does not appear to be significant, it exemplifies that more sustainable decisions could be attained.

Even though, according to the literature studied, land taxes might consist on effective tools to control urban sprawl, land values are too low amid most municipalities and only included as part of the Municipal Property Tax (IMI), that considers the area surrounding the construction, as a land tax per se is not part of the fiscal burden thus full costs are not included (Almeida *et al.,* 2013; Autoridade Tributária e Aduaneira, 2016b).

Regarding transport costs, energy taxes (specially on motor fuels) constitute the great share of environmental taxes in Portugal. In addition, road user charges are being extended (EC, 2016). Fuel taxes are amongst the highest in Europe, though it has been hypothesized that these are not the most efficient counter-sprawl measures due to the relatively inelastic demand (Ortuño-Padilla and Fernández-Aracil, 2013). The CIM Região de Aveiro (2013) report proposes a reduction of public transport fares as to encourage the use of public transport. Integrated tickets that include multiple means of public transport and companies are seen as an objective to, among others, promote the transfer to more green transportation. The objective is to maintain the supply of public transport above 30%, with added schedules and improved conditions. Moreover, it recognises the necessity to encourage walking and bicycle use (only 4%) through the expansion of appropriate infrastructures and links with public transport. These measures are expected to be implemented by 2023, with a total investment of 376 million euros and subsidized by the EU (see CIM Região de Aveiro (2013, 2014) for an overview). Moreover, the current system considers reduced fares for students and elderly, being the income reductions left in charge of the city council (Câmara Municipal de Aveiro, 2016). However, there still is a scope for improvement in Portugal's transportation policy, as it is not the most efficient since private car use is still not discouraged and public transport systems still have problems concerning accessibility and frequency (Prates and Melo, 2009).

4. Methods

This Section provides the description of the original mathematical model (Section 4.1) as well as its adaptation to test the effectiveness of the chosen economic instruments that aim to curb or steer urban sprawl (Section 4.2). Moreover, the data used in the model is presented, including city data and taxes/subsidy parameters (Section 4.3).

4.1. SULD description

The Sustainable Urbanizing Landscape Development (SULD; based on Roebeling *et al.*, 2007a) decision support tool represents a hedonic pricing simulation model that has been developed to inform sustainable urban and peri-urban development (see Roebeling *et al.*, 2017). SULD has been used to assess: i) the environmental-economic impacts of population growth and urban development on water pollution and marine ecosystems (Roebeling et al., 2007a), ii) the socio-economic impacts of location-specific urban green/blue space and infrastructure projects on urban development patterns (Roebeling *et al.*, 2014a, 2017), iii) the impacts of urban sprawl on the real estate market (Alves, 2014), iv) the socio-economic consequences of population decline in medium-sized cities (Saraiva *et al.*, 2016), v) the economic and social benefits of green and blue spaces in changing urban patterns (Grossi, 2015; Roebeling *et al.*, 2016), and vi) the contribute of regional plans in costal urbanizing management (Silva, 2016). Regarding the objectives of the present study, that is to assess the effectiveness of different economic instruments (a property tax, a land tax and a public transport subsidy) in constraining urban sprawl, SULD will be adapted and used as it is an economic model that is particularly suited to evaluate such economic instruments (Wu, 2001, 2006; Wu and Platinga, 2003). Note that this model for the City of Aveiro has calibrated and validated in Saraiva *et al*. (2016).

SULD is based on a classic analytical economic model developed by Alonso and Mills (see Mills, 1981; O'Sullivan, 2000; Wu and Platinga, 2003), that assumes the existence of a central business district (CBD) where services are provided and from which transport costs increase with distance. Consequently, households choose their residential location closest to the CBD (as far as possible within the available budget), and land values and housing costs decrease with distance from CBD. It is based on hedonic pricing theory that, building on household willingness-to-pay for goods and services, estimates implicit prices of desired features using property sales data (Roebeling *et al.,* 2007a). Hedonic models are, increasingly, used as a primary approach to assess implicit prices of environment-related goods (Schapfer *et al.,* 2015). In general, SULD assumes that housing location choice is dependent on a commitment between multiple factors – i.e.: i) balancing welfare from distance to city centre (e.g. services and job offer), ii) desired amenities (e.g. green and blue spaces), iii) residential space, iv) consumption of other goods and services, iv) development costs, and v) construction density.

SULD is a spatially explicit Geographic Information System (GIS) based model, which allows for the inclusion of information and territorial representation considering spatial connections and heterogeneous features. It, thus, considers spatial location decisions, commuting distances and choice of residential location, being more reliable for that reason (Morollón *et al.,* 2016; Tscharaktschiew and Hirte, 2011). Also, it is a simulation model (based on hedonic pricing theory) rather than a statistical model (based on observed data), meaning that scenario simulations can foresee changes (related to, among others, land-use, household type distribution, real estate values and population densities) that have not yet been observed in practice (Roebeling *et al.,* 2014b, 2016a). SULD does not require large amounts of existing data, being useful to evaluate projects, measures and policies that have not yet been applied and allowing comparisons between different possible scenarios – leading to more informed and sustainable decisions (Roebeling *et al.,* 2016b; Saraiva *et al.*, 2016; Silva, 2016) and reducing uncertainty associated with these decisions (Pinto, 2008).

The classic model includes, thus the **demand** side (Eq.1) which is represented by households, considering their preferences regarding certain goods and services, as residential space *S*, other goods and services *Z*, and environmental amenities *e*. The utility obtained by households in each location depends on their preferences, distance to environmental amenities and income *y*. Hence, households aim to maximize their utility *U* at a certain location *i,* subject to the budget constraint *y*, that is spent on housing ($p_i^h S$), other goods and services (*Z*), and transportation between the residential area and the urban centre ($p_x x$) (see Roebeling *et al.* (2014a)):

$$\underset{S_i, Z_i}{Max}\, U_i\left(S_i, Z_i\right) = S_i^{\mu} Z_i^{(1-\mu)} e_i^{\varepsilon} \tag{1}$$

$$\text{subject to } \; y = p_i^h S_i + Z_i + p_x x_i \tag{1a}$$

where p_i^h is the rental price of housing, p_x the commuting cost and x_i the road-network distance to the closest urban centre. Moreover, μ is the elasticity of demand for residential space (S_i) and ε is the elasticity of utility with respect to environmental amenities (e_i). The environmental amenity level e_i that households obtain at location *i* is decreasing with (straight-line) distance from the amenity sources (see Roebeling *et al.*, 2017),

The household's bid-rent price for housing p_i^{h*} at location *i* can now be derived (see Wu and Plantinga (2003) for a detailed derivation):

$$p_i^{h*} = \left(\frac{\mu^{\mu} (1-\mu)^{(1-\mu)} e_i^{\varepsilon} (y - p_x x_i)}{u} \right)^{\frac{1}{\mu}} \tag{2}$$

where *u* corresponds to a certain utility level *U*. The above equation provides the household's maximum willingness to pay for housing (p_i^{h*}) at location *i*, thus representing the demand side of the real estate market.

The **supply** side (Eq.3) is represented by real-estate developers, that aim to maximize their profit by trading off returns from housing development density *D* and associated development costs, that are subject to households' willingness to pay for housing. Hence, developers aim to maximize their profit (π) at a certain location *i*, which is given by the difference between construction revenue ($p^h D$) and development costs ($I+D^{\eta}$):

$$\underset{D_i}{Max}\, \pi_i(D_i) = p_i^h D_i - (l_i + D_i^{\eta}) \tag{3}$$

$$\text{with } D_i = n_i S_i$$

where p_i^h is the rental price of housing, l_i the opportunity cost of land, D_i^{η} the construction cost function (where η is the ratio of housing value to non-construction costs; Wu, 2006), n_i the household density and S_i the residential space.

The developer's bid-price for land r_i^{**} at location *i*, can now be derived (see Wu and Plantinga (2003) for a detailed derivation):

$$r_i^{**} = \left(m p_i^{h**} \right)^{\frac{\eta}{\eta - 1}} \tag{4}$$

where $m = [(\eta - 1)^{(\eta-1)/\eta}]/\eta$. This equation determines the minimum rental price for housing the developer is willing to accept (p_i^{h**}) at location *i,* thus representing the supply side of the housing market. This means that developers will only develop when residential land rents ($p_i^h D_i$) are larger than the opportunity cost of development (l_i + D_i^η), which corresponds to the foregone land rents (l_i) and investments in land conversion (D_i^η).

In **equilibrium** (Eq.5) supply for housing equals demand for housing (i.e. p_i^{h*} = p_i^{h**}). The land rent price r_i at location *i* can now be derived using Eq. (2) and (4) (see Wu and Plantinga (2003) for a detailed derivation):

$$r_i = \left(\frac{k e_i^{\varepsilon} \left(y - p_x x_i \right)}{u} \right)^{\frac{\eta}{\mu(\eta-1)}} \tag{5}$$

where $k = (\mu m)^{\mu} (1 - \mu)^{(1-\mu)}$. The corresponding optimal household density n_i at location *i* is thus given by:

$$n_i = \frac{D_i}{S_i} \tag{6}$$

with $S_i = \frac{\mu(y - p_x x_i)}{p_i^{h*}}$ the necessary condition for optimality U_i and with $D_i = (\eta - 1)^{-\frac{1}{\eta}} (r_i)^{\frac{1}{\eta}}$ the necessary condition for optimality of π_i and where p_i^{h*} and r_i are given in Eq. (2) and (5), respectively.

The equilibrium land rent price r_i and household density n_i at a certain location *i* are then derived, providing development patterns for a certain population size and composition and given the location of urban centres and environmental amenities location. SULD builds on a numerical application of the above-described model, using GAMS (General Algebraic Modelling System) 21.3 (Brooke *et al.,* 1998). The objective function maximizes, for a given household population Q_t, the difference between benefits *B* from residential (L_i^{res}) and non-residential (L_i^{nres}) land uses and development costs (l_i + D_i^η) over all locations *i*, so that:

$$\underset{L_i}{Max} B(L_i) = \sum_i \left(l_i L_i^{nres} + (r_i - l_i - D_i^{\eta}) L_i^{res} \right) \tag{7}$$

with $Q_t = \sum_i n_i$ and $L_i^{res} + L_i^{nres} = a_i$, and where l_i is represents the opportunity cost of land, r_i is the land rent price and a_i corresponds to the grid-cell area at location *i*. Land use conversion can happen between residential and non-residential land uses – the remaining land uses are fixed.

4.2. SULD adaptation

The original SULD model (see Section 4.1) does not consider property taxes, land taxes or public transport subsidies. In order to assess the effectiveness of these economic incentive instruments, SULD is adapted such that it allows to assess a flat and linear property tax, a flat and linear land tax, and a public transport cost subsidy for low-income as well as low and middle-income households.

The **demand** side (from Eq.1) is affected by the property tax (τ^{prop} or $\tau^{prop}x_i$) and public transport subsidy (σ^{trans}), through the budget constraint (Eq.1'a and Eq.1'b), as follows:

$$\underset{S_i, Z_i}{Max} U_i(S_i, Z_i) = S_i^{\mu} Z_i^{(1-\mu)} e_i^{\varepsilon} \tag{1}$$

$$\text{subject to} \quad y = p_i^h (1 + \tau^{prop}) S_i + Z_i + p_x (1 - \sigma^{trans}) x_i \tag{1'a}$$

$$y = p_i^h (1 + \tau^{prop} x_i) S_i + Z_i + p_x (1 - \sigma^{trans}) x_i \tag{1'b}$$

where τ^{prop} (in percentage) is the flat property tax (Eq.1'a) and $\tau^{prop}x_i$ is the linear property tax (Eq.1'b), and where σ^{trans} (in percentage) is the public transport subsidy that can be applied to different household groups (Eq.1'a and Eq.1'b).

The household's bid-rent price for housing p_i^{h*} at location *i* is now given by:

$$p_i^{h*} = \left(\frac{\mu^{\mu} (1-\mu)^{(1-\mu)} e_i^{\varepsilon} \left(y - p_x (1 - \sigma^{trans}) x_i \right)}{u} \right)^{\frac{1}{\mu}} \Big/ \left(1 + \tau^{prop} \right) \tag{2'a}$$

$$p_i^{h*} = \left(\frac{\mu^{\mu}(1-\mu)^{(1-\mu)} e_i^{\varepsilon}\left(y - p_x(1-\sigma^{trans})x_i\right)}{u} \right)^{\frac{1}{\mu}} \Big/ \left(1+\tau^{prop}x_i\right) \qquad (2'b)$$

where Eq.2'a corresponds to the household's bid-rent price considering a flat property tax and Eq.2'b corresponds to the household's bid-rent price considering a linear property tax. Thus, property taxes decrease and public transport subsidies increase household's maximum willingness to pay for housing (p_i^{h*}) at location *i*.

The **supply** side (from Eq.3) is affected by the land tax (τ^{land}), as follows:

$$\underset{D_i}{Max}\, \pi_i(D_i) = p_i^h D_i - \left(l_i(1+\tau^{land}) + D_i^{\eta}\right) \qquad (3'a)$$

$$\underset{D_i}{Max}\, \pi_i(D_i) = p_i^h D_i - \left(l_i(1+\tau^{land}x_i) + D_i^{\eta}\right) \qquad (3'b)$$

where τ^{land} (in percentage) is the flat land tax (Eq.3'a) and $\tau^{land}x_i$ is the linear land tax (Eq.3'b). Hence, developers will only develop when residential land rents ($p_i^h D_i$) are larger than the opportunity cost of development ($l_i(1+\tau^{land}) + D_i^{\eta}$ or $l_i(1+\tau^{land}x_i) + D_i^{\eta}$).

The **equilibrium** (Eq.5) is affected by the public transport subsidy (σ^{trans}) and the property tax (τ^{prop} or $\tau^{prop}x_i$) as follows:

$$r_i = \left(\frac{ke_i^{\varepsilon}[y - p_x(1-\sigma^{trans})x_i]}{u}\right)^{\frac{\eta}{\mu(\eta-1)}} \qquad (5')$$

where $k = (\mu m)^{\mu}(1-\mu)^{(1-\mu)}$, and the corresponding optimal household density n_i at location *i* is given by:

$$n_i = \frac{D_i}{S_i} \qquad (6)$$

with $$S_i = \frac{\mu[y - p_x(1-\sigma^{trans})x_i]}{[p_i^h(1+\tau^{prop})]^*}$$

or $$S_i = \frac{\mu[y - p_x(1-\sigma^{trans})x_i]}{[p_i^h(1+\tau^{prop}x_i)]^*}$$

the necessary conditions for optimality U_i and with $D_i = (\eta - 1)^{-\frac{1}{\eta}}(r_i)^{\frac{1}{\eta}}$ the necessary condition for optimality π_i, and where $p_i^{h^*}$ and r_i are given in Eq.2'a, Eq.2'b and Eq.5', respectively.

The above adaptations lead, in turn, to the following adaptation in the numerical application of SULD, being affected by the land tax (τ^{land} or $\tau^{land}x_i$), as follows:

$$\underset{L_i}{Max} B(L_i) = \sum_i (l_i L_i{}^{nres} + (r_i - l_i(1 + \tau^{land}x_i) - D_i{}^{\eta})L_i{}^{res}) \quad (7\text{'a})$$

$$\underset{L_i}{Max} B(L_i) = \sum_i (l_i L_i{}^{nres} + (r_i - l_i(1 + \tau^{land}x_i) - D_i{}^{\eta})L_i{}^{res}) \quad (7\text{'b})$$

with $Q_t = \sum_i n_i$ and $L_i{}^{res} + L_i{}^{nres} = a_i$.

4.3. Scenario description

4.3.1. Economic instrument 1 (Property tax)

In the Aveiro region, the property tax (municipal tax on property - IMI) ranges between 0.30% and 0.45%, with higher values in central areas (e.g. in the City of Aveiro) and lower values in less central areas (e.g. in Águeda) (Autoridade Tributária e Aduaneira, 2016). While the IMI (τ^{IMI}) is charged over the total real estate value (*Vi*), in SULD the property tax (τ^{prop}) is charged over the (annual) real estate rental value (land rent price r_i; see Section 4.2). The corresponding real estate rental tax is calculated as follows:

$$\tau^{prop} = \tau^{IMI}V_i \big/ \rho V_i \quad (8)$$

where ρV_i is the (annual) rental/mortgage payment at interest rate ρ. Given an interest rate of 5%, a τ^{IMI} of 0.5% thus corresponds to a τ^{prop} of 10%.

Scenario simulations are performed for IMIs ranging between 0.125% (τ^{prop} = 2.5%) to 0.5% (τ^{prop} = 10.0%) – comprising rates currently practiced in the region as well as providing sufficient variation to extrapolate further reductions or increases. In particular, the following three types of property tax scenarios are considered:

1. Flat property tax (τ^{prop}), i.e. equal tax rate across space, of 2.5%, 5% and 10%;
2. Increasing property tax ($\tau^{prop} x_i$) i.e. linearly increasing with road distance from urban centres, from 5% near the urban centres to 10% furthest away from urban centres; and
3. Decreasing property tax ($\tau^{prop} x_i$), i.e. linearly decreasing with road distance from urban centres, from 10% near the urban centres to 5% furthest away from urban centres.

The increasing property tax simulation is performed as it is expected to increase demand for housing near urban centres and, thus, discourage urban sprawl. The decreasing property tax simulation is performed as it represents the current situation, where property taxes in the City of Aveiro are higher than in the surrounding areas, and is expected to encourage urban sprawl instead of containing it.

4.3.2. Economic instrument 2 (Land tax)

In the Aveiro region, there is no land tax per se, as its value is only included as part of the IMI levied. This means that land costs are too low in this region, about 530€/ha/year (Almeida *et al.,* 2013; Autoridade Tributária e Aduaneira, 2016b; Roebeling *et al*., 2014). However, a land tax (τ^{land}) is included in SULD, increasing the opportunity cost of land (l; see Section 4.2). In particular, the following two types of land tax scenarios are considered:

1. Flat land tax (τ^{land}), i.e. equal tax rate across space, of 50%, 100% and 200%;
2. Increasing land tax ($\tau^{land} x_i$), i.e. linearly increasing with road distance from urban centres, where the value is the lowest, 530€, with a raise of 300€/Km, 400€/Km and 500€/Km up to the maximum distance to the urban centres.

The flat land tax simulation is performed since it will expectably increase generally the current low land costs, hence discouraging further construction especially if larger space is taken up. The increasing land tax simulation is performed as it is expected to raise land costs, especially further away from urban centres in order to prevent new constructions outside the already constructed areas, promoting urban compactness as the land costs are lower in central areas.

4.3.3. Economic instrument 3 (Public transport subsidy)

In the Aveiro region, the public transport subsidies are more commonly provided to students and elderly (Câmara Municipal de Aveiro). The income subsidies in this sector are however proposed (CIM Região de Aveiro, 2013), as it is thought to provide benefits for households that commute near central areas where the public transport network is more efficient and to discourage private car use, an urban sprawl driver. Thus, a public transport subsidy (σ^{trans}) is included in SULD, reducing the transport costs over the households bid-rent price for housing ($p_i^{h^*}$, see Section 4.2). In particular, the following two types of public transport subsidy scenarios are considered:

1. Public transport subsidy provided to low income households (σ^{trans}), i.e. equal reductions of 10%, 25% and 50% to all low income households;
2. Public transport subsidy provided to low and middle income households (σ^{trans}), i.e. equal reductions of 10%, 25% and 50% to both low and middle income households.

The public transport subsidy simulation is performed as it is expected to contribute to urban compactness as it will discourage private car use and promote commuting near central areas where the service provided is more efficient. However, the classical model does not consider different means of transport on the commuting patterns/costs. For this reason and bearing the above in mind, some assumptions were made in order to simulate a public transport subsidy, as only low and middle income households were subsidized as high income households usually do not use public transport to commute (Tscharaktschiew and Hirte, 2011).

4.4. Model parameters

The total population living in the study area is 26 078, and the total number of households is 10 991 which corresponds to an average of 2.39 persons/household (INE, 2012; see Saraiva *et al.*, 2016). The population comprises three social groups (based on INE, 2012; see Table 3): low income households (Res1) that represent 19% of the population (earning 8% of total income); middle income households (Res2) that represent 69% of the population (earning 64% of total income); and high income households (Res3) that represent the remaining 12% of the population (earning 27% of total income). Finally, housing expenditures (as a percentage of household income) range between 23.5% for low income households, 23.0% for middle-income households and 21.4% for high-income households (INE, 2012; see Saraiva *et al.*, 2016).

Table 3. Households in the City of Aveiro review (calibration parameters) (INE, 2012; source: Saraiva *et al.*, 2016)

Parameter	Unit	Res1	Res2	Res3	Total	Average
Population	#	4 929	18 046	3 101	26 078	-
Household size	##/hh	2.39	2.39	2.39	-	2.39
Households (Q)	#	2 062	7 551	1 298	10 911	-
Household income (y)	€/year	9 473	19 849	49 155	$233.2\text{x}10^6$	-
Housing expenditures (μ)	%	23.5	23.0	21.4	-	22.6

The study area comprises the larger area (21.4 km^2) surrounding the City of Aveiro (~3 km^2), bordered by the Ria de Aveiro lagoon on the north, three satellite villages on the north and east (Aradas, São Bernardo and Esgueira) and agricultural areas on the east (see Fig. 9; see Saraiva *et al.*, 2016). Large part of land use is urban residential (red in Fig. 8) and industrial/commercial (purple), surrounded by open space/agricultural (orange), forest (green) and water (blue). The area comprises several environmental amenities, including the Rossio Garden (#1), the University of Aveiro campus gardens (#2), the Santo António Park (#3) and water features (#4). Furthermore, there are several urban centres (see the white dots in Fig.8): the historical city centres, shopping centres (Fórum, Glicínias and Taboeira), the University of Aveiro and the railway station (see Saraiva *et al.*, 2016).

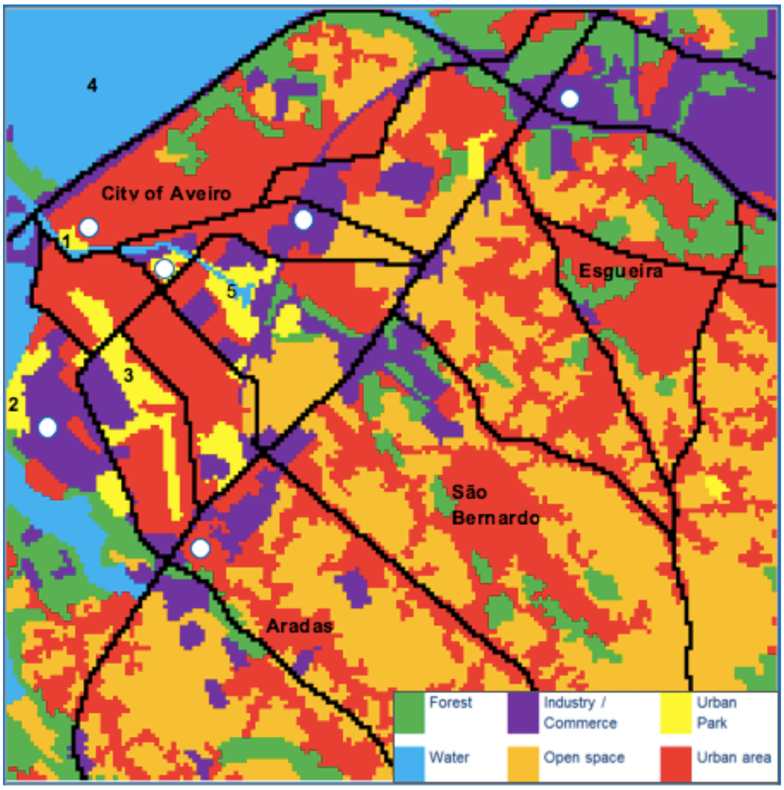


Fig.8. Land use in and around the City of Aveiro study area (EEA, 2009; source: Roebeling *et al.,* 2014b).

The study area is covered by a grid layer of 185 by 185 (a total of 35 225 cells), in which each cell is 25 m by 25 m (see Saraiva *et al.*, 2016). The levels of utility are u = 3 175 (Res1), u = 6 652 (Res2) and u = 16 475 (Res3), with the same appreciation for environmental amenities (ε=0.08) and β=1.0 (following Wu, 2001, 2006). The annual transport costs (p_x) are considered 250€/Km, which represents 11% of the expendable income (INE, 2012). Moreover, the opportunity cost of land (l) is 530€/ha/year (Roebeling *et al.*, 2014) and the considered construction costs are η=1.50 (provided average real estate values of 876€/m^2 and construction costs of 450€/m2 to 650€/m^2 in Central Portugal) (all values for 2012; INE, 2012; see Saraiva *et al.*, 2016).

To create the base-scenario, reproducing existing conditions, model parametrization, calibration and validation was performed by Saraiva *et al.* (2016). Model calibration was performed for levels of household utility *u* (the only non-observable parameter), and the degree of approximation was validated by comparing modelled and observed patterns. To this end, land use (EEA, 2009, see Fig.8) quantity and location disagreement indicators were used (Pontius Jr *et al.,* 2004). It was shown that the model performs well, with the number of urban land use cells overestimated by 6% (quantity disagreement) and the location of urban cells being correct in 79% of cases (location agreement).

5. Results

This section presents the results of the scenario simulations performed for the city of Aveiro. This includes the base scenario results (Section 5.1) and, next, the scenario simulation results (Section 5.2) with, respectively, the property tax (Section 5.2.1), land tax (Section 5.2.2.) and public transport subsidy (Section 5.2.3).

5.1. Base scenario results

The base scenario results (Table 4 and Fig.9) show that the dominant land use is agriculture (with 986 ha or 46.1% of the study area), followed by urban (333ha), industry/commerce (250ha) and forest (230ha) land uses. Within the urban land use, middle-income households (Res2) occupy the largest area (254 ha or 76.3% of the total urban area), in accordance with the fact that this social group represents the largest number of households (18 046 persons or 69.2% of the total population).

Table 4. Base scenario simulation results.

Variable	Base	Variable	Base
Land use:		**Housing quantity:**	
Forest (ha)	230	Res1 (1000m^2)	63.4
Water (ha)	156	Res2 (1000m^2)	695.0
Agriculture (ha)	986	Res3 (1000m^2)	158.8
Industry/Commerce (ha)	250	Total (1000m^2)	917.2
Urban park (ha)	56	**Living space:**	
Roads (ha)	128	Res1 (m^2/hh)	88.5
Urban		Res2 (m^2/hh)	166.6
Res1 (ha)	44	Res3 (m^2/hh)	274.9
Res2 (ha)	254	Average (m^2/hh)	164.7
Res3 (ha)	36	**Real estate value:**	
Total (ha)	333	Res1 (€/m^2/yr)	24.2
Total	2139	Res2 (€/m^2/yr)	26.3
Population:		Res3 (€/m^2/yr)	37.4
Res1*	4929	Average (€/m^2/yr)	27.2
Res2*	18046	Total (m€/yr)	50.8
Res3*	3103		
Total	26078		

Note: * Res1= Low income households; Res2= Middle income households; Res3= High income households.

Regarding housing quantity data (square meters of built area), middle-income households (Res2) occupy the largest area ($695*10^3$ m^2), followed by high-income (Res3; $159*10^3$ m^2) and low-income (Res1; $63*10^3$ m^2) households. Note that Res3 occupy 17% of the housing quantity and represent only 12% of the population, while Res1 occupy only 7% of the housing quantity and represent 19% of the population. Hence, Res3 live in least densely populated areas (less than 2.5 hh/gridcell) and Res1 live in most densely populated areas (over 3.5 hh/gridcell). These results are consistent with household (hh) living space, where largest living spaces are held by Res3 (275 m^2/hh) and smallest living spaces are held by Res1 (89 m^2/hh). Average household living space is 165 m^2/hh.

Real estate (rental) value are, as expected, largest for Res3 (37 €/m^2/yr) and lowest for Res1 (24 €/m^2/yr); average real estate (rental) values equal 27 €/m^2/yr. Real estate values are higher especially near environmental amenities (waterfronts and urban parks; up to 43 €/m^2/yr), where higher income households (Res2 and Res3) are located and population density is lower. Middle income households are, also, located on the periphery of the city, where they have larger dwellings and face lower population density. Real estate values are lower near main roads and urban centres (e.g. shopping centres and railway station; up to 20 €/m^2/yr), where low-income households (Res1) are located. The total real estate (rental) value equals 50.8 m€/yr.

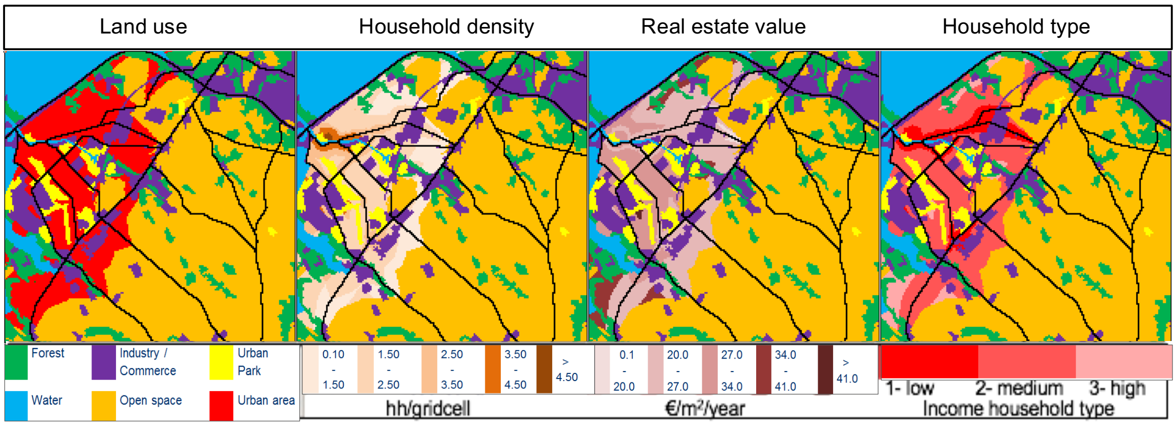


Fig.9. Base scenario land use, household density, real estate value and household type maps.

5.2. Scenario simulation results

The main objective of the present study is to assess policy instruments that aid in curbing urban sprawl. Thereby, it is expected that urban land use decreases, with a corresponding increase in agricultural/open space areas. Moreover, population density and real estate values are expected to increase while, on the other hand, housing quantity and living space are expected to decrease. Scenario simulations include a flat and linear property tax (Section 5.2.1), a flat and linear land tax (Section 5.2.2) and a public transport cost subsidy for low income as well as low and middle-income households (Section 5.2.3).

5.2.1. Property tax

A property tax was applied with the following values: 2.5%, 5% and 10% (i.e. equivalent to 0.125%, 0.25% and 0.5% IMI rate). These percentages were applied as a flat property tax (i.e. equal tax rate over the entire study area), a linearly increasing property tax (i.e. tax rate increasing with road distance from urban centres; from 5% to 10%) and a linearly decreasing property tax (i.e. tax rate decreasing with road distance from urban centres; from 10% to 5%). The current rate of IMI in Aveiro city is about 4.5% (close to the 10% of the simulated property tax), while the IMIs tend to be lower in the surrounding villages (e.g. 0.3% in Águeda and 0.35% in Estarreja; Autoridade Tributária e Aduaneira, 2016a). Results for the flat property tax scenario simulations are given in Table 5 and Fig.10 (see also Annex 1), and results for the linearly varying property tax scenario simulations are given in Table 6 and Fig.11 (see also Annex 2).

Flat property tax

Application of a flat property tax (2,5%, 5% and 10%; see Table 6) leads to a decrease in urban area (up to -46ha or -14%) and, hence, an increase in agricultural area (up to +46ha or +5%). Households move closer to main roads, urban centres and/or environmental amenities, resulting in urban contraction on the periphery of the city (see Fig.10). I.e., the property tax leads to additional expenses and, hence, all households seek to reduce expenses by reducing living space and/or commuting costs.

Household distribution changes due to the implementation of the property tax (see Fig.10). High-income households move from the southern and northern periphery to areas near environmental amenities; middle income households move from the northern and eastern periphery to areas near main roads; and low income households move even closer to main roads and urban centres. Responses are stronger for Res3, as they own larger living spaces and, thus, the property tax weighs more in the budget constraint (see Eq.1'a). As a consequence, the total built area (housing quantity) decreases by up to almost 24%, with lowest decreases observed for low income households (up to -18%) and largest decreases observed for high income households (up to -25%). Similarly, living space decreases by up to -11%, ranging between -9% for low income households and -11% for high-income households (see Table 6). Hence, a general increase in population density can be observed (up to +2 hh/gridcell) – in particular around main roads, urban centres and/or environmental amenities (see Fig.10).

Real estate (rental) values increase, on average, by up to 12% due to the implementation of the flat property tax. As mentioned above, all households move closer to main roads, urban centres and/or environmental amenities – i.e. competition for these attractive areas increases and, thus, boosts real estate values. Real estate (rental) values increase most for higher income households (by up to almost +13%), with local increases of up to 70% near environmental amenities (Fig.10) where high-income households crowd-out lower income households. Real estate (rental) values for low-income households increase by up to 10%. The total real estate (rental) value shows a small increase (up to +0.3%), to 50.9 m€/yr. The overall impact of the flat property tax is a contraction of the urban area.

Table 5. Flat property tax scenario (2.5%, 5% and 10%) simulation results.

Variable	Base	2.5% Property Tax		5% Property Tax		10% Property Tax	
Land use:							
Agriculture (ha)	986	999	1.3%	1011	2.5%	1032	4.7%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	42	-2.7%	41	-5.1%	39	-9.9%
Res2 (ha)	254	244	-4.0%	234	-7.8%	217	-14.5%
Res3 (ha)	36	34	-4.5%	33	-8.0%	30	-15.3%
Total (ha)	333	321	-3.9%	309	-7.5%	287	-13.9%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Housing quantity:							
Res1 (1000m^2)	63.4	60.1	-5.2%	57.2	-9.8%	51.8	-18.3%
Res2 (1000m^2)	695.0	647.1	-6.9%	602.6	-13.3%	528.1	-24.0%
Res3 (1000m^2)	158.8	147.0	-7.4%	137.8	-13.3%	119.8	-24.6%
Total (1000m^2)	917.2	854.2	-6.9%	797.6	-13.0%	699.7	-23.7%
Living space:							
Res1 (m^2/hh)	88.5	86.3	-2.5%	84.2	-4.9%	80.3	-9.3%
Res2 (m^2/hh)	166.6	161.7	-2.9%	157.1	-5.7%	148.7	-10.7%
Res3 (m^2/hh)	274.9	266.3	-3.1%	258.9	-5.8%	244.2	-11.2%
Average (m^2/hh)	164.7	159.9	-2.9%	155.5	-5.6%	147.2	-10.6%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.8	2.6%	25.4	5.2%	26.7	10.4%
Res2 (€/m^2/yr)	26.3	27.1	3.1%	27.9	6.3%	29.5	12.5%
Res3 (€/m^2/yr)	37.4	38.6	3.2%	39.7	6.2%	42.1	12.6%
Average (€/m^2/yr)	27.2	28.0	3.0%	28.8	6.1%	30.5	12.1%
Total (m€/yr)	50.8	50.8	0.1%	50.9	0.2%	50.9	0.3%

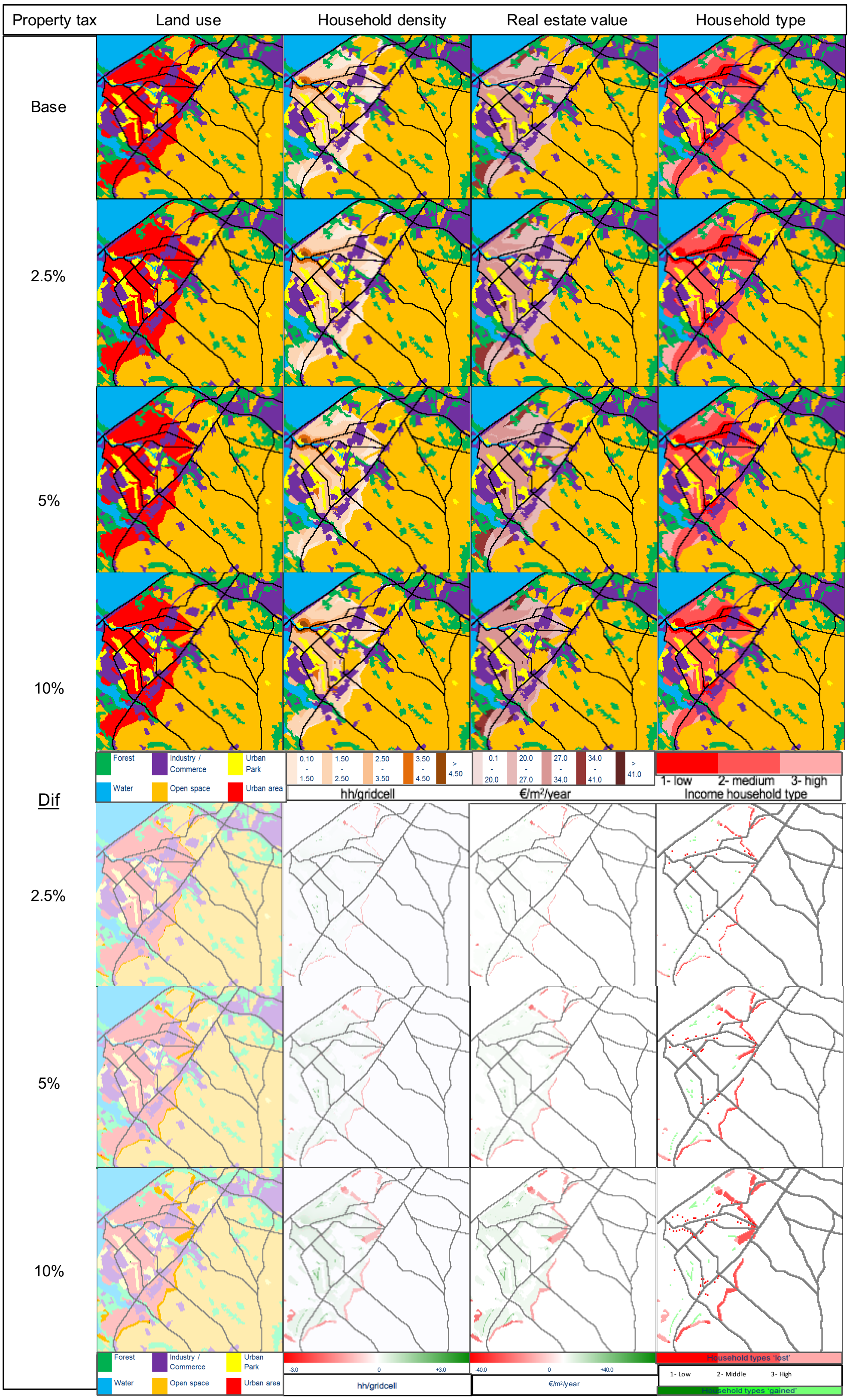


Fig.10. Flat property tax scenario (2.5%, 5%, and 10%) land use, household density, real estate value and household type maps and corresponding difference maps.

Linear property tax

Two variations of distance-dependent property taxes are assessed, a linearly increasing property tax (increasing with road distance from urban centres) and a linearly decreasing property tax (decreasing with road distance from urban centres), and discussed in the following sub-sections.

Linearly increasing property tax

Application of the linearly increasing property tax (i.e. tax rate increasing with road distance from urban centres; from 5% to 10%) results in a decrease in urban area (-42ha or -13%) and a respective increase in agricultural area (+42ha or +4%). Households move closer to main roads, urban centres and/or environmental amenities (see Fig.11), following the same pattern as the flat property tax. I.e., housing expenses increase and, hence, households reduce expenditures by reducing living space and/or commuting costs.

Household distributional changes include (see Fig.11): high income households relocate from the southern and northern peripheries to more central areas near environmental amenities; middle income households relocate from the northern and eastern peripheries to areas near main roads; and, similarly, low income households move even closer to main roads and central areas. Effects are most significant for middle income households, as they live further from urban centres (implying a higher property tax rate) and own larger living spaces (implying larger housing expenses; see Eq.1'b). Consequently, the total built area (housing quantity) decreases by around 21%, with largest decreases observed for middle income households (around -23%) and smallest decreases for high income households (around -15%). Likewise, living space decreases by around -9% ranging between -8% for high income households and -10% for middle income households. Therefore, a general increase in population density is observed (up to +2 hh/gridcell) around main roads, urban centres and/or environmental amenities (see Fig.11).

Real estate (rental) values increase, on average, by around -11% due to the implementation of the linearly increasing property tax. Households move closer to main roads, urban centres and/or environmental amenities, where competition for housing increases and, thus, boosting real estate values up to +68% in these areas. Increases are largest for middle income households (almost +12%) and smallest for high income households (around +8%). The total real estate (rental) value increases by +0.4% (to 51.0

m€/yr). The overall impact of the linearly increasing property tax is, also, a contraction of the urban area.

Linearly decreasing property tax

Application of the linearly decreasing property tax (i.e. tax rate decreasing with road distance from urban centres; from 10% to 5%) results in a general decrease in urban area (-28ha or -8%) and a corresponding increase in agricultural area (+28ha or around +3%). Again, households relocate from the periphery closer to main roads, urban centres and/or environmental amenities – resulting in urban contraction that is somewhat lower as compared to the previous two property taxes as tax charges are now higher near urban centres and lower further away from urban centres (see Fig.11).

Household distributional impacts are different as compared to the previous property tax scenarios (Fig.11). High income households relocate more strongly to more attractive central areas, while middle income households relocate less strongly from the eastern periphery to areas near main roads and low income households relocate less strongly to areas near main roads. High income households buy-out lower income households that face a higher tax burden they cannot easily afford (as they live closer to urban centres and main roads) – enabling high income households to move closer to more central areas near environmental amenities (being able to bear the high tax burden, even if that means smaller living spaces). The total built area decreases (-16%), especially for high income households (-37%) and least so for low income households (-10%). Living space also decreases (-7%), ranging from -14% for high income households to -5% for low income households. Thus, there is a somewhat smaller increase in population density (up to +2 hh/gridcell) namely around main roads, urban centres and/or environmental amenities (Fig.11).

Real estate (rental) values increase, on average, by 6% due to the implementation of the linearly decreasing property tax. Due to the increase in housing costs, in particular high-income households trade larger houses for smaller ones in more attractive central areas – thus increasing competition for areas near urban centres and environmental amenities. Hence, the real estate value increases from 6% (low income households) up to 16% (high income households), with local increases of up to +65% near environmental amenities. The total real estate (rental) value remains unchanged (50.8 m€/yr). The overall impact of the linearly increasing property tax is a slight contraction of the urban area.

Hence, the 5%-10% tax resulted into a larger urban land, housing quantity and living space reduction as well as agriculture land, real estate and floor number increase than the 10%-5% tax (see Table 6 and Annex 2). While the impacts suffered where bigger for middle income households in the first, the latter posed a more significant impact on high income households, accordingly to the area that suffered the highest increase in housing costs. The effects were more significant in the linear 5%-10%, only outweighed by the flat 10% tax, despite the latter having a more severe social impact. On the other hand, the linear 10%-5% and the flat 5% tax had more similar outcomes (Table 6 and Annex 2).

Table 6. Linear (5%-10% and 10%-5%) and flat (5% and 10%) property tax scenario simulation results.

Variable	Base	Linear 5%-10% Property Tax		Linear 10%-5% Property Tax		5% Property Tax		10% Property Tax	
Land use:									
Agriculture (ha)	986	1028	4.3%	1014	2.8%	1011	2.5%	1032	4.7%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%	128	0.0%
Urban									
Res1 (ha)	44	39	-9.7%	41	-5.4%	41	-5.1%	39	-9.9%
Res2 (ha)	254	219	-14.0%	238	-6.2%	234	-7.8%	217	-14.5%
Res3 (ha)	36	33	-8.1%	26	-27.5%	33	-8.0%	30	-15.3%
Total (ha)	333	291	-12.8%	305	-8.4%	309	-7.5%	287	-13.9%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%	2139	0.0%
Housing quantity:									
Res1 (1000m^2)	63.4	52.0	-17.9%	56.8	-10.4%	57.2	-9.8%	51.8	-18.3%
Res2 (1000m^2)	695.0	535.6	-22.9%	612.5	-11.9%	602.6	-13.3%	528.1	-24.0%
Res3 (1000m^2)	158.8	134.8	-15.1%	99.8	-37.1%	137.8	-13.3%	119.8	-24.6%
Total (1000m^2)	917.2	722.5	-21.2%	769.1	-16.1%	797.6	-13.0%	699.7	-23.7%
Living space:									
Res1 (m^2/hh)	88.5	80.6	-9.0%	83.9	-5.2%	84.2	-4.9%	80.3	-9.3%
Res2 (m^2/hh)	166.6	150.1	-9.9%	156.8	-5.9%	157.1	-5.7%	148.7	-10.7%
Res3 (m^2/hh)	274.9	254.3	-7.5%	236.5	-14.0%	258.9	-5.8%	244.2	-11.2%
Average (m^2/hh)	164.7	149.3	-9.3%	152.5	-7.4%	155.5	-5.6%	147.2	-10.6%
Real estate value:									
Res1 (€/m^2/yr)	24.2	26.6	10.0%	25.5	5.6%	25.4	5.2%	26.7	10.4%
Res2 (€/m^2/yr)	26.3	29.3	11.5%	27.9	6.4%	27.9	6.3%	29.5	12.5%
Res3 (€/m^2/yr)	37.4	40.4	8.2%	43.4	16.1%	39.7	6.2%	42.1	12.6%
Average (€/m^2/yr)	27.2	30.2	11.1%	28.9	6.4%	28.8	6.1%	30.5	12.1%
Total (m€/yr)	50.8	51.0	0.4%	50.8	0.0%	50.9	0.2%	50.9	0.3%

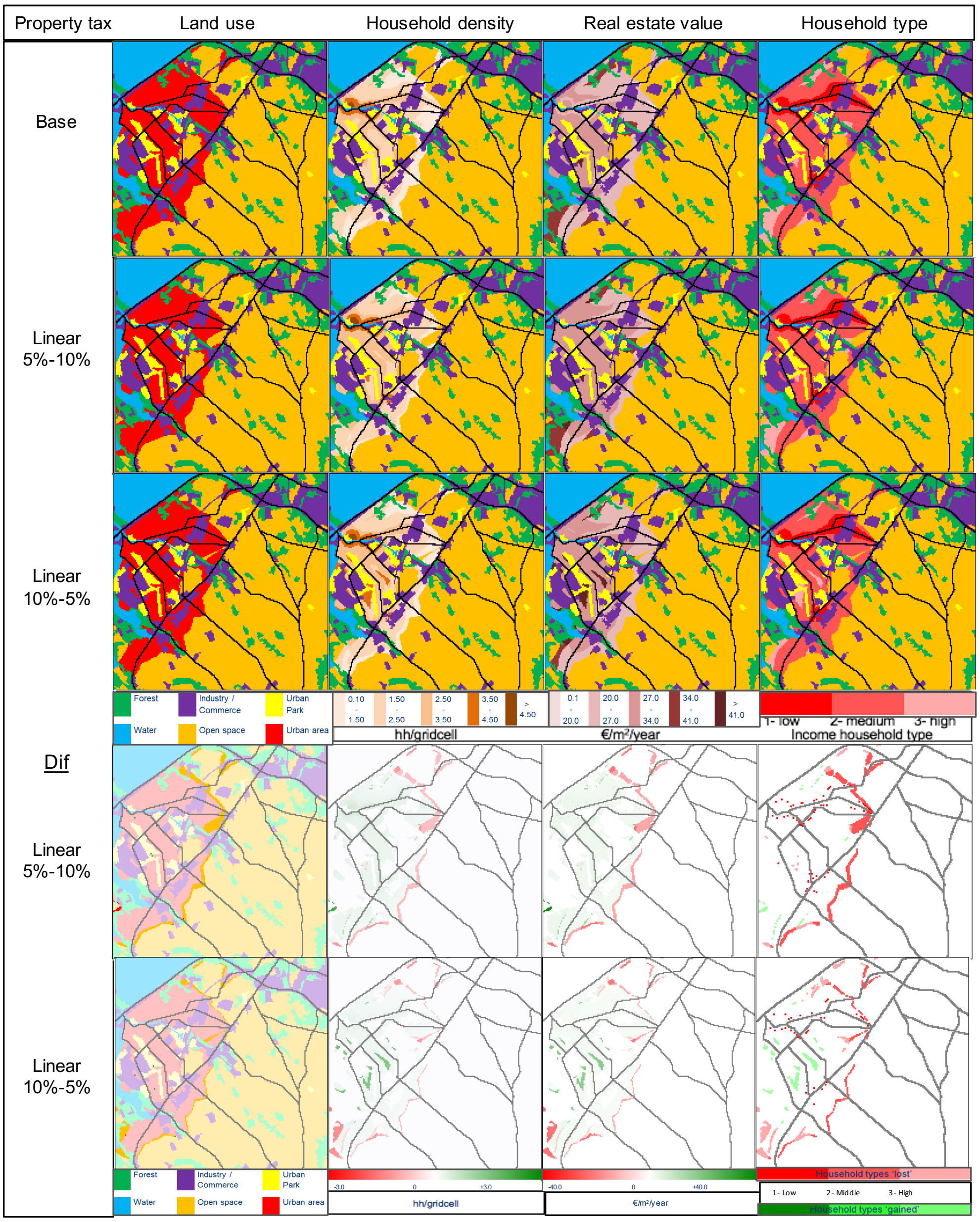


Fig.11. Linear property tax scenario (5%-10%, 10%-5%) land use, household density, real estate value and household type maps and corresponding difference maps.

5.2.2. Land tax

Two types of land taxes are assessed. First, a flat land tax with increases in the opportunity cost of land (*l*) by 50%, 100% or 200% over the entire study area. Secondly, a linearly increasing land tax (i.e. tax rate increases with road distance from urban centres; increasing by 300€/km, 400€/km and 500€/km from the base opportunity cost of land). The current, base, opportunity cost of land (*l*) is 530€/ha/year (Roebeling *et al*., 2014; see Section 4.4). Results for the flat land tax scenario simulations are given in Table 7 and Fig.12 (see also Annex 3), and results for the linearly increasing land tax scenario simulations are given in Table 8 and Fig.13 (see also Annex 4).

Flat land tax

Application of a flat land tax (50%, 100% and 200%) has virtually no effect on the urban (0ha or -0.1%) and agricultural area (0ha or 0%), regardless of the tax burden. Minor relocations between households takes place, in particular across middle and high income households. The tax burden is, however, not sufficient to significantly encourage urban contraction (the land tax charges reach a maximum of 0.15€/m^2/yr).

Household distributional changes are minimal (see Fig.12). Few middle income households move from the periphery closer to urban centres, leaving relatively attractive areas for high income households. Accordingly, the total built area (housing quantity) remains unchanged – with some decreases for low and middle income households (up to -0.8%) that are counterbalanced by small increases for high income households (up to +4%). Similarly, average living space remains unchanged – with no changes for low income households, some reductions for middle income households (up to -0.2%) and small increases for high income households (up to almost +0.9%). Overall, changes in population density are negligible (see Fig.12).

Real estate (rental) values hardly change due to the implementation of the flat land tax. Real estate (rental) values somewhat increase for middle income households (up to +0.2%) and somewhat decrease for high income households (up to -0.9%). The overall impact of the flat land tax is a near imperceptible contraction of the urban area.

Table 7. Flat land tax scenario (50%, 100% and 200%) simulation results.

Variable	Base	50% Land Tax		100% Land Tax		200% Land Tax	
Land use:							
Agriculture (ha)	986	986	0.0%	986	0.0%	986	0.0%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	44	-0.1%	44	-0.1%	44	-0.1%
Res2 (ha)	254	253	-0.3%	253	-0.4%	253	-0.5%
Res3 (ha)	36	36	1.5%	37	2.1%	37	2.7%
Total (ha)	333	333	-0.1%	333	-0.1%	333	-0.1%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Housing quantity:							
Res1 ($1000m^2$)	63.4	63.3	-0,1%	63.3	-0.1%	63.3	-0.1%
Res2 ($1000m^2$)	695.0	692.0	-0.4%	690.7	-0.6%	689.5	-0.8%
Res3 ($1000m^2$)	158.8	161.8	1.9%	163.0	2.7%	164.3	3.5%
Total ($1000m^2$)	917.2	917.2	0.0%	917.1	0.0%	917.2	0.0%
Living space:							
Res1 (m^2/hh)	88.5	88.5	0.0%	88.5	0.0%	88.5	0.0%
Res2 (m^2/hh)	166.6	166.4	-0.1%	166.3	-0.1%	166.3	-0.2%
Res3 (m^2/hh)	274.9	276.3	0.5%	276.8	0.7%	277.4	0.9%
Average (m^2/hh)	164.7	164.8	0.0%	164.8	0.0%	164.8	0.1%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.2	0.0%	24.2	0.0%	24.2	0.0%
Res2 (€/m^2/yr)	26.3	26.3	0.1%	26.3	0.2%	26.3	0.2%
Res3 (€/m^2/yr)	37.4	37.2	-0.5%	37.1	-0.7%	37.1	-0.9%
Average (€/m^2/yr)	27.2	27.2	0.1%	27.2	0.1%	27.2	0.1%
Total (m€/yr)	50.8	50.8	0.0%	50.8	0.0%	50.8	0.0%

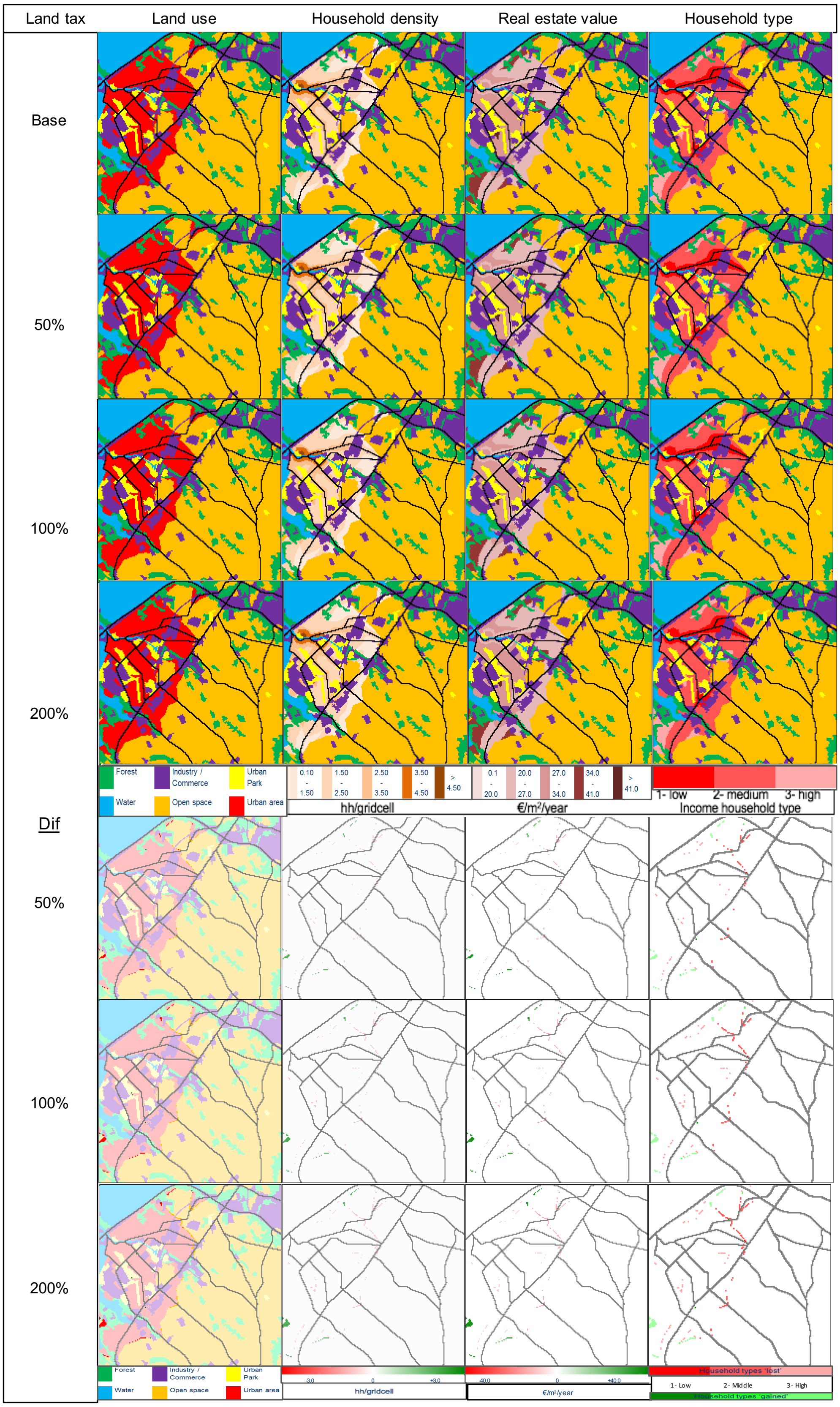


Fig.12. Flat land tax scenario (50%, 100%, 200%) land use, household density, real estate value and household type maps and corresponding difference maps.

Linearly increasing land tax

Application of the linearly increasing land tax (i.e. base opportunity cost of land plus 300€/km, 400€/km and 500€/km road distance from urban centres) results in an increase in urban area (up to +8ha or +2%) and a respective decrease in agricultural area (up to -8ha or -0.8%). Results are somewhat controversial as this tax leads to an increase in urban area, with some urban areas contracting though others expanding. In particular, households move from least accessible areas closer to main roads as to reduce the tax burden.

Household distributional changes (see Fig.13) include the relocation of high income households from more exclusive areas (away from main roads and near environmental amenities) to somewhat less exclusive areas (closer to main roads and more central environmental amenities), thereby reducing livings space, housing costs, tax burden and, to a minor extent, transport costs. Low and middle income households relocate from peripheral areas (away from main roads) and sprawl into areas around main roads, thereby reducing tax burden and housing costs while increasing living space and transport costs. As a consequence, the total built area (housing quantity) increases by almost +3%, ranging from a large decrease for high income households (up to -12%) to a significant increase for low and middle income households (up to +6%). Effects on living space are smaller (up to +0.2%), with small increases for high income households (up to +3%) and some increases for low and middle income households (up to +1%). Hence, population density increases around more central environmental amenities (up to +1 hh/gridcell) and around main roads in the peripheral sprawl area (up to +1 hh/gridcell) (see Fig.13).

Real estate (rental) values decrease, on average, by around -1.3% due to the implementation of the linearly increasing land tax. This is in line with the relocation of high income households described above, with increased demand in more central areas (namely near environmental amenities) and around main roads in the periphery (up to +3% increase in real estate values). In the peripheral sprawl area, occupied by low and middle income households, demand around less attractive main roads is smaller (up to -1.6% decrease in real estate values). As a consequence, the total real estate (rental) value decreases to 50.6 m€/yr (-0.3%). The overall impact of the linearly increasing land tax is an expansion of the urban area (i.e. the expansion of low and middle income households exceeds contraction of high income households).

Table 8. Linear land tax scenario (300€/Km, 400€/Km and 500€/Km) simulation results.

Variable	Base	300€/Km Land Tax		400€/Km Land Tax		500€/Km Land Tax	
Land use:							
Agriculture (ha)	986	979	-0.7%	979	-0.7%	978	-0.8%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	45	2.8%	45	3.2%	45	3.6%
Res2 (ha)	254	262	3.3%	263	3.5%	263	3.7%
Res3 (ha)	36	33	-8.8%	32	-9.3%	32	-9.6%
Total (ha)	333	340	1.9%	341	2.1%	341	2.2%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Housing quantity:							
Res1 (1000m^2)	63.4	63.3	4.6%	66.8	5.3%	67.2	6.0%
Res2 (1000m^2)	695.0	729.5	5.0%	732.1	5.3%	733.4	5.5%
Res3 (1000m^2)	158.8	141.2	-11.1%	140.1	-11.8%	139.6	-12.1%
Total (1000m^2)	917.2	937.1	2.2%	938.9	2.4%	940.3	2.5%
Living space:							
Res1 (m^2/hh)	88.5	89.1	0.6%	89.2	0.7%	89.3	0.8%
Res2 (m^2/hh)	166.6	168.1	0.9%	168.2	1.0%	168.3	1.0%
Res3 (m^2/hh)	274.9	266.8	-3.0%	266.2	-3.2%	266.0	-3.2%
Average (m^2/hh)	164.7	164.9	0.1%	164.9	0.1%	165.0	0.2%
Real estate value:							
Res1 (€/m^2/yr)	24.2	23.9	-1.2%	23.8	-1.4%	23.8	-1.6%
Res2 (€/m^2/yr)	26.3	25.9	-1.3%	25.9	-1.4%	25.9	-1.4%
Res3 (€/m^2/yr)	37.4	38.5	3.1%	38.6	3.3%	38.6	3.4%
Average (€/m^2/yr)	27.2	26.9	-1.2%	26.8	-1.3%	26.8	-1.3%
Total (m€/yr)	50.8	50.6	-0.3%	50.6	-0.3%	50.6	-0.3%

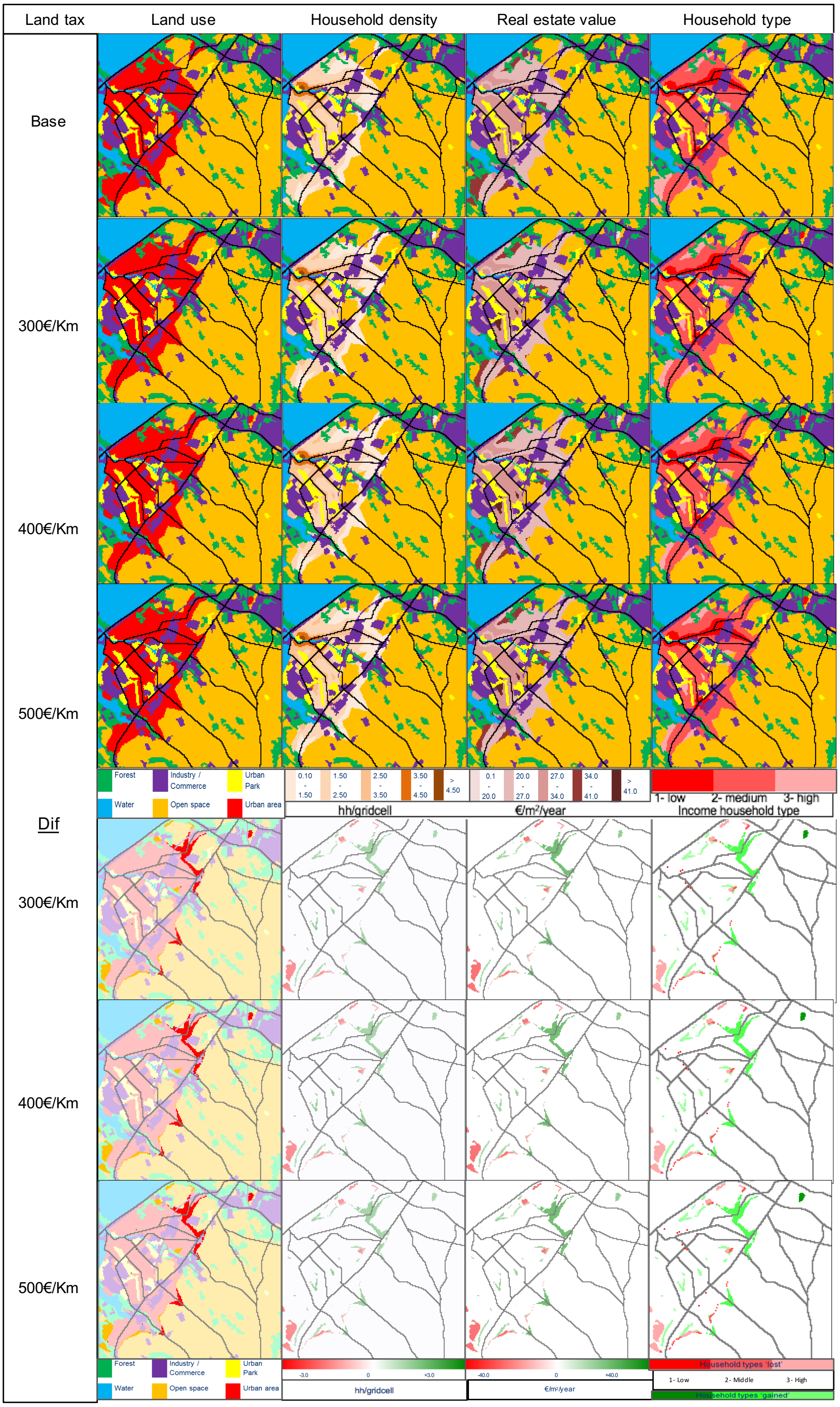


Fig.13. Linear land tax scenario (300€/Km, 400€/Km, 500€/Km) land use, household density, real estate value and household type maps and corresponding difference maps.

5.2.3. Public Transport subsidy

A public transport subsidy is applied with the following values: 10%, 25% and 50%. These subsidies are provided to, first, only low income households (see Table 9, Fig.14 and Annex 5) and, second, both low and middle income households (see Table 10, Fig.15 and Annex 6).

Low income household public transport subsidy

Application of the public transport subsidy for low income households (10%, 25% and 50%; see Table 9), leads to a decrease in urban area (up to -10ha or -3%) and, corresponding increase in agricultural area (up to +10ha or +1.1%). For the 10% and 25% subsidy scenario, all households contract around more central and/or attractive areas; for the 50% subsidy scenario this also occurs though, now, low income households move to areas on the periphery and, corresponding, middle income households move to areas around main roads and urban centres. I.e., the public transport subsidy loosens the budget constraint of low income households – allowing more attractive housing locations (10% and 25% subsidy) or larger living spaces (50% subsidy).

Regarding the household distribution (Fig.14), for the 10% and 25% subsidy scenarios all households slightly contract (up to -4%) – with low income households benefiting most from the public transport subsidy by moving to more attractive areas in the city (buying-out middle income households). For the 50% subsidy scenario, low income households resettle on the urban fringe (north, east and south) – buying-out middle income households that are forced to contract and condense in the city. Low and middle income households are most strongly affected, as the increase in expandable income of low income households is spent to improve housing conditions (location or size; see Eq.1'a) and, hence, low income households compete more severely with middle income households. As a consequence, the total built area (housing quantity) decreases by up to more than -8%, with high income households experiencing a gradual decrease (up to -3%), middle income households experiencing first a gradual decrease (up to -1.8%) and then a significant decrease (-17%), and low income household experiencing first a gradual decrease (up to -5%) and then a significant increase (about +71%). Similarly, living space decreases by up to -1.3%, with high income households experiencing gradual reductions (up to -0.7%), middle income households experiencing first a gradual (up to -0.4%) and then a significant (-4%) reduction, and low income household experiencing first a gradual decrease (up to -1.1%) and then a significant increase (+15.3%; see Table 9). Regarding population density, for the 10% and the 25% subsidy scenarios no major changes are observed; for the 50% subsidy scenario a decrease in population density is observed in areas near main roads and urban centres (up to -1 hh/gridcell) while an increase in population density is observed in areas on the periphery of the city (up to +1 hh/gridcell; see Fig.14).

Real estate (rental) value increase, on average, by up to +0.7% due to the implementation of the public transport subsidy for low income households. High income households experience a gradual increase (up to +0.7%), middle income households experience first a gradual (up to +0.5%) and then a significant (+5%) increase, and low income household experience first a gradual increase (up to +1.6%) and then a significant decrease (-12%). The total real estate (rental) value shows a small increase (up to +0.8%), to 51.2 m€/yr. The overall impact of this public transport subsidy is a small contraction of the urban area.

Table 9. Low income household public transport subsidy scenario (10%, 25% and 50%) simulation results.

Variable	Base	10% Public Transport Subsidy		25% Public Transport Subsidy		50% Public Transport Subsidy	
Land use:							
Agriculture (ha)	986	988	0.2%	991	0.6%	996	1.1%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	43	-2.2%	42	-4.1%	66	51.7%
Res2 (ha)	254	253	-0.5%	251	-1.3%	222	-12.7%
Res3 (ha)	36	36	-0.4%	36	-0.8%	35	-2.1%
Total (ha)	333	331	-0.7%	328	-1.6%	323	-3.1%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Housing quantity:							
Res1 (1000m^2)	63.4	61.7	-2.7%	60.3	-5.0%	108.2	70.6%
Res2 (1000m^2)	695.0	690.7	-0.6%	682.4	-1.8%	577.4	-16.9%
Res3 (1000m^2)	158.8	157.9	-0.5%	157.1	-1.0%	154.4	-2.8%
Total (1000m^2)	917.2	910.3	-0.8%	899.8	-1.9%	840.0	-8.4%
Living space:							
Res1 (m^2/hh)	88.5	88.0	-0.6%	87.6	-1.1%	102.1	15.3%
Res2 (m^2/hh)	166.6	166.3	-0.1%	165.9	-0.4%	160.1	-3.8%
Res3 (m^2/hh)	274.9	274.5	-0.1%	274.2	-0.3%	273.0	-0.7%
Average (m^2/hh)	164.7	164.4	-0.2%	164.0	-0.5%	162.6	-1.3%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.4	0.8%	24.5	1.6%	21.2	-12.4%
Res2 (€/m^2/yr)	26.3	26.3	0.2%	26.4	0.5%	27.6	5.1%
Res3 (€/m^2/yr)	37.4	37.4	0.1%	37.5	0.3%	37.6	0.7%
Average (€/m^2/yr)	27.2	27.3	0.3%	27.4	0.6%	27.4	0.7%
Total (m€/yr)	50.8	50.8	0.0%	50.8	0.1%	51.2	0.8%

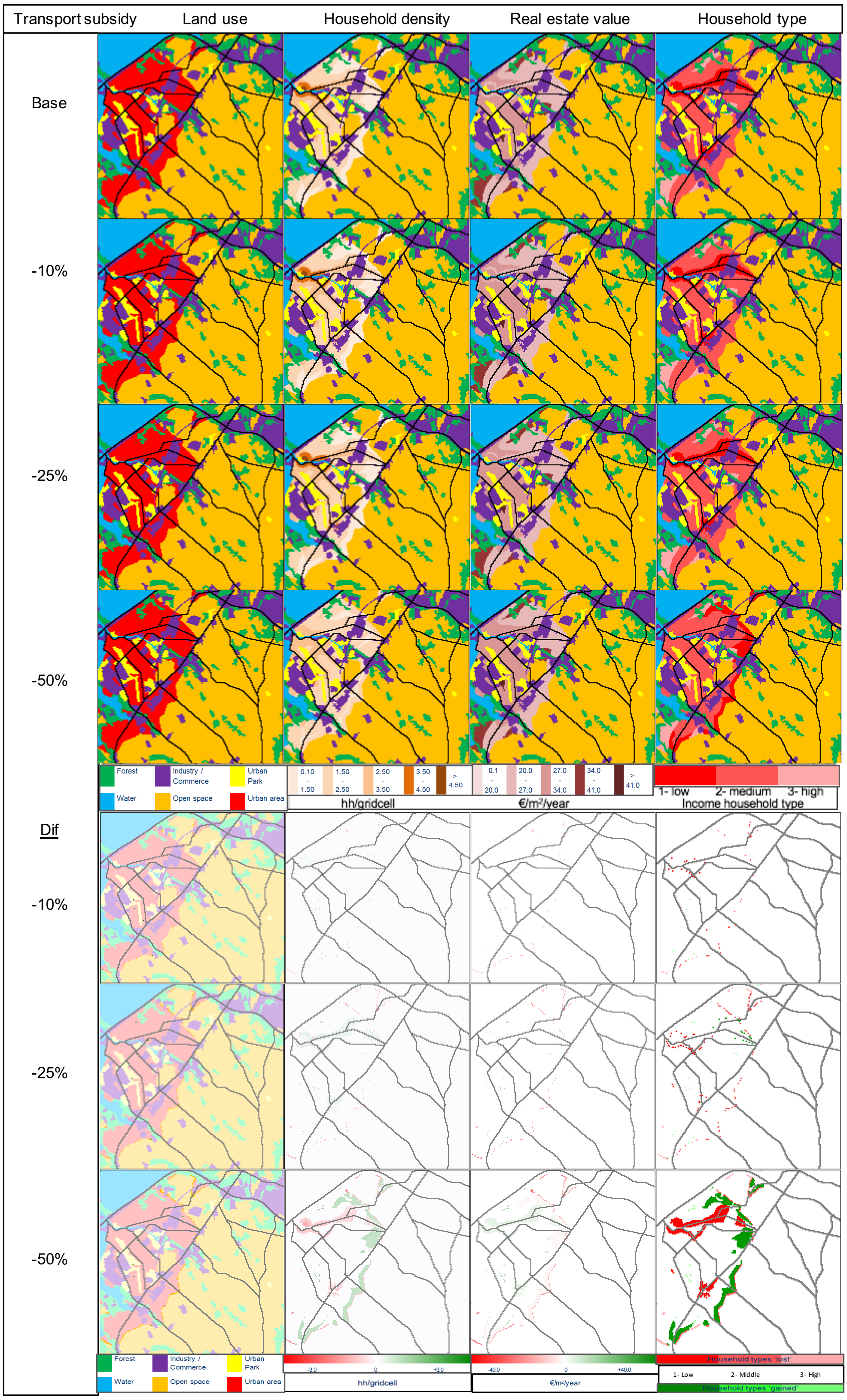


Fig.14. Low income households public transport subsidy scenario (-10%, -25%, -50%) land use, household density, real estate value and household type maps and corresponding difference maps.

Low and middle income household public transport subsidy

Application of the public transport subsidy for low and middle income households (10%, 25% and 50%; see Table 10), leads to a decrease in urban area (up to -60ha or -18%) and a respective increase in the agricultural area (up to +61ha or +6%). For all simulated scenarios, all households contract around main roads, urban centres and/or environmental amenities. I.e., the public transport subsidy loosens the budget constraint of low and middle income households- enabling more attractive housing locations or larger living spaces. This is in line with the fact that, with lower commuting costs, households can move inwards to more desirable locations or larger living spaces.

As for the household distribution, all subsidy scenarios (10%, 25% and 50%; see Fig.15), low income households relocate gradually with the increasing tax burden from central to more peripheral areas, immediately before the contraction area abandoned by middle income households, in a way that both groups benefit from the public transport subsidy by moving to more attractive areas (contraction up to -16%). This is because low income households are able to improve their housing conditions with more budget available, moving to more peripheral areas; while middle income households, also with more income available to spend on housing (Eq.1'a), are able to relocate to more central areas, competing with the high income households (buying them out and forcing them to condense, up to -41%). High income households hence move to more attractive areas in city left by middle income households. Responses are stronger for high income households that face a strong competition from lower income households, who have more currency and thus do not have to live in the suburbs where housing is cheaper. Consequently, the total built area (housing quantity) decreases up to almost -26%, ranging between -50% for high income households and -17% for low income households. Likewise, average living space suffers a decrease up to almost -7%, between -4% for low income households and -15% for high income households (Table 10). Therefore, a general increase in the population density is verified (up to +1 hh/gridcell), namely in more central areas: main roads, urban centres and/or environmental amenities (see Fig.15).

Regarding real estate (rental) values, an average increase up to +7% could be observed due to the application of the public transport subsidy. As mentioned above, households move inwards, increasing the competition for these attractive areas which increased the real estate values up to +20%, with local increases of up to +73% near environmental amenities. Contrarily, low income households experience the lowest increases (up to +5%).

The total real estate (rental) value shows a small increase of almost +1.8%, to 51.7 m€/yr. Overall impact was a large contraction of the urban area.

Annexes 7, 8, 9, 10, 11 and 12 show the same results data but distributed by level of subsidy (10%, 25% and 50%) in each household type, with the complete table, maps and differences maps for each. The patterns are the same, however it is highlighted that the effects are always more evident when applied to both lower and middle households than only to lower households.

Table 10. Low and middle income household public transport subsidy scenario (10%, 25% and 50%) simulation results.

Variable	Base	10% Public Transport Subsidy		25% Public Transport Subsidy		50% Public Transport Subsidy	
Land use:							
Agriculture (ha)	986	1000	1.4%	1019	3.3%	1047	6.2%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	42	-2.6%	41	-6.9%	38	-13.0%
Res2 (ha)	254	243	-4.5%	231	-8.9%	213	-16.0%
Res3 (ha)	36	34	-3.9%	29	-20.1%	21	-40.7%
Total (ha)	333	320	-4.2%	301	-9.9%	273	-18.3%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Housing quantity:							
Res1 (1000m^2)	63.4	61.3	-3.3%	57.8	-8.9%	52.8	-16.7%
Res2 (1000m^2)	695.0	653.8	-5.9%	614.0	-11.7%	550.7	-20.8%
Res3 (1000m^2)	158.8	150.9	-5.0%	118.6	-25.3%	79.4	-50.0%
Total (1000m^2)	917.2	866.0	-5.6%	790.4	-13.8%	683.0	-25.5%
Living space:							
Res1 (m^2/hh)	88.5	87.9	-0.7%	86.9	-1.9%	85.4	-3.6%
Res2 (m^2/hh)	166.6	164.4	-1.3%	162.4	-2.5%	158.9	-4.6%
Res3 (m^2/hh)	274.9	271.1	-1.4%	254.6	-7.4%	233.4	-15.1%
Average (m^2/hh)	164.7	162.7	-1.2%	159.1	-3.4%	153.9	-6.6%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.4	1.0%	24.8	2.7%	25.5	5.4%
Res2 (€/m^2/yr)	26.3	26.7	1.7%	27.2	3.6%	28.0	6.8%
Res3 (€/m^2/yr)	37.4	37.8	1.2%	40.2	7.5%	44.8	19.8%
Average (€/m^2/yr)	27.2	27.6	1.6%	28.1	3.4%	29.0	6.7%
Total (m€/yr)	50.8	50.9	0.3%	51.1	0.6%	51.7	1.8%

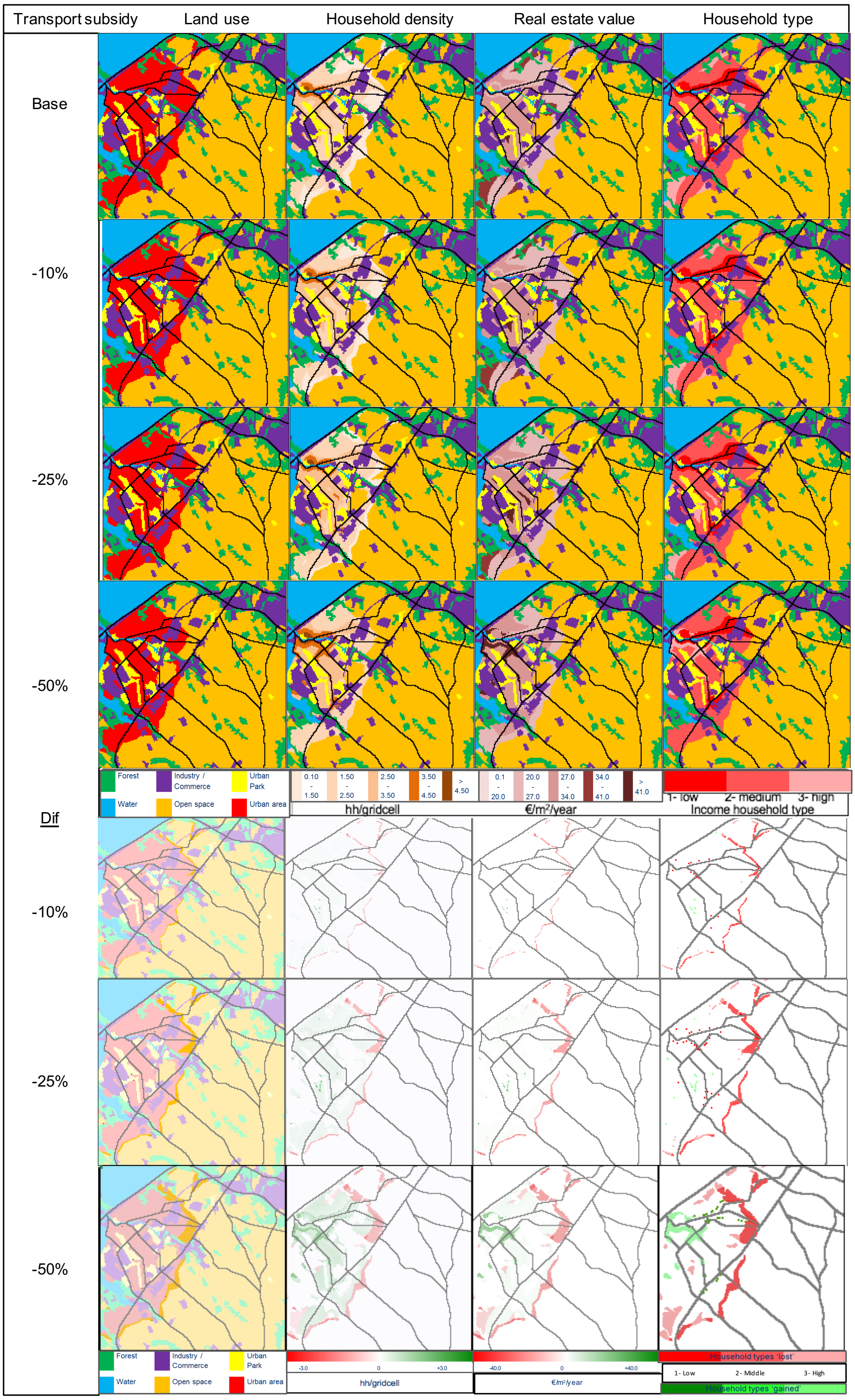


Fig.15. Low and middle income households public transport subsidy scenario (-10%, -25%, -50%) land use, household density, real estate value and household type maps and corresponding difference maps.

6. Discussion

This section discusses the performed economic incentive scenario simulations that aim to prevent the conversion of rural into urban land uses. This study focused on economic instruments because, according to Prates and Melo (2009), command and control instruments alone have been proven inefficient in addressing urban sprawl, transport and land use issues in Portugal. Despite all the laws and programmes, there is still visible a lack in sustainable and consistent planning in Portugal, with recurrent loss of investments and thus opportunities resulting in environmental degradation. This planning shortage might lead to the destruction of natural resources (Pinto, 2008). So, it is extremely necessary that strong policies continue to appear. After a complete research on the existing literature available, a property tax, a land tax as well as a public transport subsidy were selected to be addressed as anti-sprawl policies. As pointed out in the literature, these themes are mostly analysed using statistical and theoretical methods while oftentimes only tested in USA settings.

Base scenario

Results for the City of Aveiro show that lower cost of living (housing and land) and the possibility to consume larger living spaces in areas further away from urban centres, are the main drivers of urban sprawl. This is in line with several studies that show living costs decrease with distance to urban centres and, thus, compensate the increasing commuting costs (Milan and Creutzig, 2016; Sexton *et al*., 2012; Wu, 2001; Wu, 2006). In the City of Aveiro, high income households live near central environmental amenities, middle income households near main roads and in the suburbs, and low income households live next to urban centres and main roads. This is consistent with: i) Wu and Platinga (2003) who found that if environmental amenities are near urban centres (such as in the City of Aveiro), that is where high income household will locate; ii) Cotteller and Peerlings (2011) who found that middle income households live on the periphery near main accessibilities; and iii) Borck and Wrede (2005) and Brueckner and Kim (2003) who found that low income households live near urban centres where construction in height takes place (Cotteller and Peerlings (2011) and Tanguay and Gingras (2011) note that high income households cannot compete with the benefits accruing from these type of constructions).

Property tax

Property tax simulations were performed applying flat, linearly increasing and linearly decreasing rates. According to EEA (2015) and Eurostat (2014), property taxes (recurrent) are amongst the more common and, furthermore, are considered to be one of the least detrimental do growth. Eurostat (2014), moreover, indicated that the Portugal fiscal scope has the potential to increase this tax. The linearly increasing property tax is in line with the proposition by Almeida *et al.* (2013), who state that property taxes in central areas should be lowest (to encourage city centre restauration) and increase towards the suburbs.

The flat property tax (2.5%, 5% and 10%) results in a decrease in urban area (up to -46ha or -14%) and a, corresponding, increase in agricultural area (up to +46ha or +5%). Although the tax does not result in great unbalanced social effects (no income group is specifically targeted), higher income groups are slightly more affected (given their larger properties and values) in terms of relocation, densification and contraction. These results are in line with Kulmer *et al.* (2014), that confirm that housing costs have key importance concerning the households' relocation choices. Real estate (rental) values increase (by up to +12%), due to the increased demand for housing near central environmental amenities (in line with Wu, 2001). Summarizing, flat property taxes lead to contraction of urban boundaries, the decrease in housing quantity and living space, and the increase in household density and real estate values.

The linearly increasing property tax follows (from 5% near urban centres to 10% furthest away from urban centres) results in a decrease in urban area (42ha or -13%) as well as an increase in agricultural area (+42ha or +4%). The tax does not result in great unbalanced social effects (no income group is specifically targeted), however middle income groups are slightly more affected (given that they lived further from city centres and owned larger houses) in terms of relocation, densification and contraction. These findings were also noted by Tanguay and Gingras (2011), that referred that if housing costs were not lower in the periphery, households would relocate to more central areas, thus higher prices near city centre would encourage households moving outwards to cheaper houses. Real estate (rental) values increase (by up to +11%), due to the increased demand for housing near central environmental amenities (as pinpointed by Wu, 2001). Summarizing, linearly increasing property taxes lead to contraction of urban boundaries, the decrease in housing quantity and living space, and the increase in household density and real estate values.

The linearly decreasing property tax follows (from 10% near urban centres to 5% furthest away from urban centres) results in a decrease in urban area (-28ha or -8%) as well as an increase in agricultural area (+28ha or +3%). The tax does result in some unbalanced social effects, as high income households are more affected). This is because high income households buy-out lower income households that face a higher tax burden they cannot easily afford (as they live closer to urban centres and main roads) – enabling high income households to move closer to more central areas near environmental amenities as they are able to bear the tax burden. This is true concerning relocation, densification and contraction. Real estate (rental) values increase (by up to +16%), due to the increased demand for housing near central environmental amenities (as referred by Wu, 2001). Summarizing, linearly decreasing property taxes lead to a smaller contraction of urban boundaries, the decrease in housing quantity and living space, and the increase in household density and real estate values.

Between the two linear taxes, the 5%-10% (linearly increasing land tax) showed a higher agriculture land and real estate (rental) values increase, a more significant reduction in land use, in housing quantity and in living space. The linear 10%-5% (linearly decreasing land tax) only posed more significant results for Res3. Hence, this shows that generally the higher tax levied on the urban fringe is more efficient for urban compactness than the opposite tax. This can be justified by the fact that, as already referred, one of the reasons for households to move to the periphery is lower housing related prices; if these are higher in city centre (as it is verified in Aveiro region), compactness is less encouraged. These findings were also noted by Tanguay and Gingras (2011), that referred that if housing costs were not lower in the periphery, households would relocate to more central areas, thus higher prices near city centre would encourage households moving outwards to cheaper houses.

Comparing the flat and the linear property tax performed, the flat 10% had more significant results for all parameters evaluated, except for the high income households, who were more affected by the linear 10%-5%. However, the differences between the 10% flat tax and the 5%-10% linear tax were short: 0.4% for the agriculture land, 1.1% on the total reduction in residential land, 2.5% on the total housing quantity, 1.3% for average living space and 1% for the average real estate value. However, the 10% flat tax is more severe for all households than the linear 5%-10%. As for the 5% flat tax and the 10%-5% linear tax, results were more similar, being the total values more notorious for the linear one, perhaps on behalf of its great impact on high income households. These findings on property tax shows that, in spite of the more significant results for the 10% flat tax and for the 10%-5% linear tax, all simulated values are in some way beneficial concerning urban sprawl control, which is in line with most of the literature analysed. Bento *et al.* (2005), Brueckner (2001), Groves (2009), Institute for Fiscal Studies (2011), Jou and Lee (2007), Milan and Creutzig (2016) and Song and Zenou (2006) all found that a property tax is an efficient anti-sprawl tool, delaying construction and consumption of housing space, accruing from the great housing costs; however, all of them either use statistical or theoretical approaches and no work was found assessing different types of property taxes. Furthermore, Song and Zenou (2009) also pinpointed that differentiated tax rates might affect the scattered development, thus lower tax rates on the suburbs induces resettlement outwards. The results are also in conformity with Kulmer *et al.* (2014), that stated that housing prices are essential regarding households' relocation choices. As for Roebeling *et al.* (2016) and Banzhaf and Lavery (2009), both did not found any significant effect of the applied tax, maybe because the first tested developing timing (not assessed in the present work) and the latter used a statistical approach. Moreover, a study conducted by Brueckner and Kim (2003) reflected that a property tax might either control, if higher prices encourage smaller dwellings or cause urban sprawl, if the number of floors or dwelling sizes is fixed, as more space is needed, which is not the case in this study. Another possible cause of expansion pinpointed by the same theoretical study is in the case of higher housing prices causing a decrease on improvements, forcing households to look for better quality houses at urban fringe, which was not assessed in the present work.

Land tax

Land tax simulations were performed applying flat, linearly increasing and linearly decreasing rates. According to EEA (2010), land price might constitute an indicator of future development, since land prices and land use patterns are connected. As the land prices are too low in Aveiro, further development might take place, so this constitutes a key sector concerning land use planning (Almeida *et al.,* 2013). Moreover, land costs increase property values, hence they are expected to control urban sprawl (Wu, 2001). The linearly increasing land tax is in line with EEA (2010) and Almeida *et al.* (2013), that referred that land prices depend on the distance to urban centres and high land prices in city centre would cause urban expansion.

The flat land tax (50%, 100% and 200%) results in virtually no alterations in the urban area (0ha or -0.1%) as well as in agricultural area (0ha or 0%). Although the tax almost has no impact on each parameter analysed, middle income households are slightly affected in terms of relocation, densification and contraction, as they had relatively larger houses. Real estate (rental) values practically remain unchanged (~0%). This is in line with the fact that development revenues continue to overcome agricultural rent, especially where land costs are too low (Almeida *et al.,* 2013; Bento *et al.*, 2005). Summarizing, flat land taxes lead to an almost imperceptible contraction of the city, as well as nearly unchanged housing quantity, living space, household density and real estate values.

The linearly increasing land tax (300€/Km, 400€/Km and 500€/Km, starting from the base real value in central areas) results in an increase in urban area (up to +8ha or +2%) and a decrease in agricultural area (up to +8ha or +1%). The tax does result in some unbalanced social effects, as high income households are more affected. This is because high income households lived further away from highways, thus where the tax burden is higher and, moreover, in larger houses, thus being forced to move closer to more central areas near environmental amenities. This is true concerning relocation, densification and contraction. Low and middle income also move to locations near highways where the applied tax is lower, being able to increase their housing quantity and living space. This was not real estate (rental) values virtually remain the same (up to -0.3%), corresponding to an increase for high income households (by up to +3%), due to the increased demand for housing near central environmental amenities and a small decrease for low and middle households (up to -1.6%), that relocate to areas where there is less demand. Summarizing, linearly decreasing property taxes lead to a smaller contraction of urban boundaries, a slight increase in housing quantity, living space, household density and a minor decrease in real estate values.

Considering both the flat and liner land tax, neither of them posed a significant impact on urban patterns. However, despite the results have proven not to be much different from the base scenario, the taxes showed different trends. On one hand, the flat land tax had practically no differences in low and middle income households, even if the small differences point out to an almost imperceptible contraction, while it caused a more visible expansion on high income households. However, the total variations on the studied area were almost non-existent. On the other hand, the linearly increasing land tax posed an opposite trend, forcing high income households to contract due to the growing land costs. However, the same tax caused low and middle income households to expand. This means that the land price is too low (Abrantes *et al*., 2016; Almeida *et al.,* 2013) currently for a simple global raise in land cost to take effect, as profits from residential use continue to overcome in a great deal the land costs. The linearly increasing land tax also did not raise the costs enough, as there still is available land to be build inside the periphery, meaning that households still manage to stay within the first increased values where distance by highway to city centre is small and so it is the tax levied. Summarizing, linearly increasing land taxes lead to the expansion of urban boundaries, the slight increase of housing quantity, living space and household density as well as a minor decrease in real estate values.

Literature available to date is ambiguous, in a way that the present results go against some of the revised findings, as a land tax is acknowledged as an efficient tool in steering urban sprawl, as reported by Altes (2008), Banzhaf and Lavery (2010), Cho *et al*. (2009), Institute for Fiscal Studies (2011), Jou and Lee (2007), Milan and Creutzig (2016) and Wu, (2001), in which increased land costs decreased the city boundary as it will increase the costs of converting agricultural land thus increasing the probability of construction in already build-up areas. However, Banzhaf and Lavery (2010), Cho *et al*. (2009), and Milan and Creutzig (2016) ground their evidences on statistical methods and the first two corresponds to USA studies. Moreover, Altes (2008) is a review work and Jou and Lee (2007) used a theoretical model, focused on development timing and neglecting environmental amenities. However, Bento *et al.* (2005), Institute for Fiscal Studies, (2011) and Wu (2006) unveiled that development will continue to occur as long as the benefit for developers outweigh the agricultural rent, which is multiple times lower- land is too cheap-, that might lead to the failure of land taxes that not provide enough incentive to delay development. Moreover, EEA (2010) and Institute for Fiscal Studies (2011) works reflexes the difficulty of valuing land in an adequate way. This concern is also addressed by Almeida *et al.* (2013), that, besides stating that land prices in Portugal are too low, the effects of land taxes tend to be unpredictable and dependent on many factors as expectation, housing density and development timing. Thus, according to Milan *et al*. (2016), literature still lacks conclusive outcomes regarding taxes designs, not existing a consensus concerning the level of tax that should be levied. EEA (2010) also expressed that the mechanisms of this taxes must still be better understood, as land prices depend on distance to urban centres, urban pressures, infrastructures and environmental amenities. The same author concludes that land taxes could be a complement but not replace entirely other land use planning instruments, namely in Europe, as there is weak evidence that land prices itself are sufficient to shape land use.

There are still several studies that assess a comparison between a property and a land tax. Despite several of them, as previously referred, recognize the value of property tax, most defend that a switch to a land tax would be socially more efficient, with less distortionary effects, as the case of Brueckner and Kim (2003), Peng and Wang (2009) and Banzhaf and Lavery (2010), although the first two works are theoretical and the latter is both a statistical and a USA study and none of them assess different taxes. Nevertheless, for a land tax the value of land must be separated from the construction value (Eurostat, 2014) while the property taxes include land, being thus less difficult to implement (EEA, 2010). Bento *et al.* (2005) takes a more conservative position, whose findings preconize that it is not possible to say if it is better than other policies, stating that a property tax may generate more revenues than a land tax and it is preferable in rural areas as it subsidizes agriculture use.

Public transport subsidy

Public transport subsidy simulations were performed providing a subsidy to low income households and to both low and middle income households. As conveyed by Tscharaktschiew and Hirte (2011), a subsidy can be delivered to different social groups, in which low income households constitute the group that mostly uses public transport, contrarily to high income households who predominantly use private car (value less time spent on commuting and are able to pay for more expensive modes of transport (Brueckner, 2003). Different rates were applied in accordance with what was proposed by Borck and Wrede (2005).

The low income household public transport subsidy (10%, 25% and 50%) results in a decrease in urban area (up to -10ha or -3%) and, corresponding increase in agricultural area (up to +10ha or +1%). Although the two lower subsidies (10%, 25%) do not result in great unbalanced social effects (no income group is specifically targeted), low income households are slightly more benefited (due to the possibility to move to more attractive areas, as conveyed by Tscharaktschiew and Hirte (2011)), which is true in terms of relocation, densification and contraction. Real estate (rental) values increase (by up to +1.6%), due to the increased demand for housing near central environmental amenities (in line with Wu, 2001). Contrarily, for the 50% public transport subsidy, an inversion took place, resulting in great unbalanced social effects, as low income households benefit the most and middle income households are severely affected, due to the increasing competition between the two groups. Thus, low income households move to the periphery, increasing its housing quantity, living space and decreasing real estate values. On the other hand, high income and especially middle income households contract, decreasing their housing quantity, living space and increasing real estate values. Summarizing, the low income household public transport subsidy resulted in a small contraction of the urban boundaries, a decrease in the housing quantity, living space and a slight increase in the real estate (rental) values.

The low and middle income household public transport subsidy (10%, 25% and 50%) results in a decrease in urban area (up to -60ha or -18%) and a respective increase in the agricultural area (up to +6ha or +6%). This subsidy led to some unbalanced social effects, as low and middle income households benefit the most and high income households are severely affected, due to the increasing competition accruing from the income availability for the subsidized groups, that no longer need to live in the suburbs where house is cheaper and start to look for locations more desirable near central areas. Real estate (rental) values increase (by up to +7%), due to the increased demand for housing near central environmental amenities (in line with Wu, 2001). Summarizing, the low and middle income household public transport subsidy lead to the contraction of urban boundaries, the decrease in housing quantity and living space, and the increase in household density and real estate values.

Comparing both subsidies simulated, it can be concluded that subsidizing low and middle income households resulted in a higher increase in agriculture land as well as a much higher total reduction on urban land, housing quantity and real estate value, as well as significant reductions concerning living space. In fact, low income public transport subsidy not only posed smaller alterations in all parameters but also resulted in an expansion of low income households, although the city itself did not expand, affecting more severely middle income households. For this reason, it can also be argued that, despite subsidizing low and middle income households affecting slightly more high income households, poses less social inequalities as all households compete between them. Contrarily, the subsidy for only low income households affected in a great deal middle income households that must compete directly with the low income ones. Literature on this subject is scarce, in a way that, no simulation model assessing only public transport subsidy and urban sprawl was found, concern pinpointed by Ambarwati *et al.* (2014). Moreover, most studies focusing on fuel costs, as Bureau (2012), Creutzig (2014), Song and Zenou (2006) and Wu (2001, 2006), all of them conducting methodologies that concluded that the raise in fuel costs is a great tool controlling urban sprawl thus leading to more compact cities. This was not assessed in this study as it is acknowledged that fuel prices will continue to rise, being necessary to find alternative policies as they will not be able to rise indefinitely (Dodson and Sipe, 2007). Besides that, findings of the same author show that rising fuel costs can be socially stressful, mainly to low income households who might not be able to use private car neither access to public transport if they locate in more remote areas or if the supply is not enough. Furthermore, Wu (2001) reflexes on the importance of encouraging public transport and Molloy and Shan (2012), Kulmer *et al.* (2014) and Rodriguez (2013) referred that changes in commuting costs are usually too small to cause households to relocate, only influencing the residents that already intended to move, despite being the first two being a theoretical assessment and the latter a statistical and USA study. On the opposite, the findings of EEA (2010) and Tscharaktschiew and Hirte (2011) are in line with results from the present work, stating that subsidies do have spatial influence. More than being environmental beneficial (EEA, 2015), public transport subsidies are acknowledged for being welfare enhancing, and to decrease private car use, contrarily to other transport subsidies that increase urban sprawl (Kulmer *et al.,* 2014; Tscharaktschiew and Hirte, 2011). Moreover, Dodson and Sipe (2007), EC (2011) and Su and DeSalvo (2008) give great importance to the quality of the service of public transport, being the frequency and periods of operation essential to encourage its use. Furthermore, Ambarwati *et al.* (2014) even refers that improving public transport is a requirement to steer urban sprawl, as if this does not happen, households will increase the private car use and hence urban sprawl. Tanguay and Gingras (2011) and Su and DeSalvo (2008) also showed that a decrease on public transportation costs increased the number of households living near the city centre and urban compactness thus reducing urban sprawl, as in the present study.

7. Conclusion and future perspectives

Urban sprawl is a widely acknowledged urban planning problem, with several and complex causes that cause city to over-expand, namely due to the lower housing and land costs on the periphery in combination with low commuting costs that allow commuting further distances. As this phenomenon results in multiple negative environmental, social and economic impacts, tools are needed to contain it and to attain a more sustainable urban planning. Hence there are several policies referred in the literature – despite these being ambiguous and without major certainties, they reveal the increased awareness for the problem. From the literature, it is clear that a recasting of the traditional policies is needed, which is possible with economic instruments that have already given proofs of their value in halting and steering urban sprawl. Economic instruments allow for the internalisation of the externalities that define urban sprawl, as the true services and values provided by nature and the environment are not considered – leading to conversion into artificial land. Hence, as various economic instruments can be adapted to control urban sprawl, some economic incentive instruments are assessed on their effectiveness – including property taxes, land taxes and public transport subsidies.

There is a lack of studies assessing such economic incentive instruments, as most approaches use statistical models based on observed data or theoretical simulation models based on abstract examples. However, real simulation models are essential to provide decision makers some grounded information on which to base future planning decisions – i.e.- ex-ante assessment enabling to experimentation of different policies for a specific area. Therefore, the overall objective of this study is to assess the effectiveness of economic instruments that aim to enhance urban sustainability as well as contain urban sprawl and its associated negative impacts, in an attempt to find the best policy. For that reason, the SULD (Sustainable Urbanizing Landscape Development) decision support tool (Roebeling *et al.*, 2007, 2017) is adapted and applied to assess the effectiveness of property taxes, land taxes and public transport subsidies in halting and steering urban sprawl in the City of Aveiro (Portugal).

The city of Aveiro is a medium-sized city on the northwest coast of Portugal. This coastal area has suffered one of the biggest increases in artificial areas in Europe, with mainly diffuse urbanization patterns. The area urgently needs planning policies as it has several components with great ecological value, namely the Ria de Aveiro Lagoon, that provide multiple economic services and values that are endangered by pollution and progressive land conversion. It is acknowledged that the low prices of land and low housing costs on the periphery in combination with the low commuting costs, are the main drivers of urban sprawl in this area. Despite the urgency, the area lacks on effective anti-sprawl measures. Even though the City of Aveiro is governed by several plans, namely the regional plans that highlight urban sprawl as a problem that should be contained, measures were sparsely adopted and there is a lack of compliance regarding protected areas. Concerning economic instruments, there is a scope to increase environmental taxations – albeit with a focus on energy only.

As for the consistency of the model, all results are as expected. Contraction of the city leads to a decrease in housing quantity, as compact cities lead to less space available for construction and, consequently, smaller living spaces. Contraction also leads to an increase in real estate values as demand for housing results in more densely populated areas and, thus, an increase in the number of floors. The opposite holds for expansion of the city, in which housing quantity and living space increase as more space becomes available. In that case, real estate values and number of floors decrease – characteristic of more disperse and rural housing conditions.

Comparison of the different economic instruments shows that the low and middle income public transport subsidy results in the biggest contraction in urban area (-18%), followed by the 10% flat property tax (-14%) and the 5%-10% linearly increasing property tax (-13%); on the contrary, the flat land tax had a negligible effect (-0.1%) and the 500€/Km linearly increasing land tax even caused an increase in urban area (+2%). Concerning housing quantity, the low and middle income public transport subsidy results in the largest decrease (-26%), followed by the 10% flat property tax (-24%) and the 5%-10% linearly increasing property tax (-21%); reversely, the flat land tax results in no changes (0%) and the 500€/Km linearly increasing land tax resuls in an increase in housing quantity (+0.2%). Considering average living space per household, the more significant increase takes place with the 10% flat property tax (-11%), followed by the 5%-10% linearly increasing property tax (-9%) and the low and middle income public transport subsidy (-7%); on the opposite, the flat land tax and the 500€/Km linearly increasing land tax lead to a slight increase in living space (+0.1% and +0.2%, respectively). Thus, it can be concluded that the low and middle income public transport subsidy results in the greatest reduction in urban area, followed by the 10% flat property tax and the 5%-10% linearly increasing property tax. Between these two property taxes, the flat property tax affects all households equally while the linearly increasing property tax affects in particular households on the outskirts of the city. On the other hand, the flat land tax does not result in a reduction in urban area while the linearly increasing land tax (namely the 500€/Km) even encourages urban sprawl.

From the above conclusions and considering the actual problematic and the results obtained, it seems clear that efforts must be made to ensure that urban sprawl is contained and thus the most efficient policies needs to be found. This study assessed three groups of economic incentive instruments, however, the results seems to contradict findings of some of the existing literature while supporting others, so it could be beneficial to perform complementary works to increase the certainty level of the conclusions and to allow more complete assessments. The public transport subsidy could be calculated in a different way, considering both private car use and other modes in the model as well as comparing the efficiency of this policy with the fuel pricing system. Moreover, the flat land tax could be levied at a higher rate and the linearly increasing land tax could be tested with circular geographical increases and not using road distance. The same reasoning can be applied to the linearly increasing property tax, with a geographical increase instead of an increase based on road distance. Furthermore, the locations that were considered as “urban centres” can be altered in some future study. Finally, simultaneous policies might be performed, assessing whether the joint effects achieve more positive impacts. However, this study enables future replication and can be considered a starting point to the uncover trends that provides some insights in the most efficient policies in steering urban sprawl, which it was concluded to be the public transport subsidy, the 10% flat property tax and the 5%-10% linearly increasing property tax.

References

Abrantes, P., Fontes, I., Gomes, E. and Rocha, J., 2016. “Compliance of land cover changes with municipal land use planning: Evidence from the Lisbon metropolitan region (1990-2007)”. *Land Use Policy*, 51, 120-134.

Almeida, J., Condessa, B., Pinto, P. and Ferreira, J.A., 2013. “Municipal Urbanization Tax and land-use management- The case of Tomar, Portugal”. *Land Use Policy*, 54, 103-115.

Alves, H.M.T.C., 2014. “Modelação da Expansão Urbana Residencial na Região da Ria de Aveiro”. *Master thesis*, Faculdade de Letras, Universidade do Porto, Porto, Portugal, 180 pp.

Altes, W.K.K., 2008. “Taxing land for urban containment: Reflections on a Dutch debate”. *Land Use Policy*, 26, 233-241.

Ambarwati, L., Verhaeghe, R., Pel, A.J. and Arem, B.V., 2014. “Controlling urban sprawl with integrated approach of space transport development strategies”. *Procedia - Social and Behavioural Sciences*, 38, 679-694.

Autoridade Tributária e Aduaneira, 2016a. “Artigo 112º - Taxas”, Informação fiscal, Códigos Tributários, CIMI, Capítulo X, Artigo 112º, Taxas, revised on: 2016/07/21, available at: http://info.portaldasfinancas.gov.pt/pt/informacao_fiscal/codigos_tributarios/cimi/ra/cimira112_032016.htm.

Autoridade Tributária e Aduaneira, 2016b. “Código do Imposto Municipal Sobre Imóveis”, 82pp.

Autoridade Tributária e Aduaneira, 2017. Portal das finanças, Consulta de Taxas IMI/CA, Aveiro, revised on: 2017/06/19, available at: https://www.portaldasfinancas.gov.pt/pt/main.jsp?body=%2Fimi%2FconsultarTaxasIMI.jsp&ano=2016&distrito=01AVEIRO

Banzhaf H.S. and Lavery, N., 2010. “Can the land tax help curb urban sprawl? Evidence from growth patterns in Pennsylvania”. *Journal of Urban Economics*, 67, 169-179.

Bento, A.M., Franco, S., F. and Kaffine, D., 2005. “The efficiency and distributional impacts of alternative anti-sprawl policies”. *Journal of Urban Economics*, 59, 121-141.

Bhatta, B., Saraswati, S. and Bandyopadhyay, D., 2010. “Urban sprawl measurement from remote sensing data”. *Applied Geography*, 30, 731-740.

Borck, R. and Wrede, M., 2005. “Political economy of commuting subsidies”. *Journal of Urban Economics*, 57, 478-499.

Bresson, G., Dargay, J., Madre, J. and Pirotte, A., 2003. “Economic and structural determinants of the demand for public transport: an analysis on a panel of French urban areas using shrinkage estimators”. *Transport Research*, 38, 269-285.

Brooke, A.D., Kendrick, A., Meeraus., A. and Raman, R., 1998. “GAMS Release 2.5: A User's Guide”. Washington, DC: GAMS Development Corporation, 276 pp.

Brueckner, J.K., 2001. “Urban sprawl: Lessons from urban economics”. Brookings- Wharton Papers on Urban Affairs, 34 pp.

Brueckner, J.K., 2003. “Transport subsidies, system choice and urban sprawl”. CESifo Working Paper, No. 1090, 31 pp.

Brueckner, J.K., Thiesse, J. and Zenou, Y., 1999. “Why is central Paris rich and downtown Detroit poor? An amenity-based theory”. *European Economic Review*, 43, 91-107.

Brueckner, J.K. and Kim H., 2003. “Urban sprawl and the property tax”. *International Tax and Public* Finance, 10, 5-23.

Bureau, D., 2012. “Public transport infrastructure, urban sprawl, and post-carbon cities”. *Recherches économiques de Louvain*, 77, 125-139.

Carvalho, J. and Pais, C., 2010. “Methodology to identify dispersed occupation on a local scale”. CITTA 3rd Annual Conference on Planning Research. Bringing City Form Back into Planning, 16 pp.

Cavailhès, J., Frankhauser, P., Peeters, D. and Thomas, I., 2009. “Residential equilibrium in a multifractal metropolitan area”. *Annals of Regional Science*, 45, 681-704.

CCDRC, 2008. “Protcentro (Plano regional de ordenamento do território centro) - Estudo temático sobre infra-estruturas de acessibilidade, transportes e logística”. CCDRC Report, March, 2008, 61 pp.

CCDRC, 2011. “Protcentro (Plano regional de ordenamento do território centro) - Proposta de PROT-CENTRO”. CCDRC Report, May 2011, 205 pp.

CENSE/FCT-UNL., 2012. “Aplicação do modelo EcoTerra: município do Barreiro”. Final Report, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa for C.M Barreiro, 25pp.

Cho, S., Kim, S. and Roberts, R.K., 2009. “Measuring the effects of a land value tax on land development”. Presentation at the Southern Agricultural Economics Association Annual Meeting, Atlanta, Georgia, January 31-February 3, 2009, 23 pp.

CIM Região de Aveiro, 2013. “Plano Intermunicipal de Mobilidade e Transportes da Região de Aveiro”. Comunidade Intermunicipal da Região de Aveiro, Phase 3/ Relatório de Planos de Ação, 444 pp.

CIM Região de Aveiro, 2014. “Plano Intermunicipal de Mobilidade e Transportes da Região de Aveiro - Relatório Síntese”. Comunidade Intermunicipal da Região de Aveiro, 200 pp.

Constanza, R., d'Arge, R., Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P. and Belt, M., 1997. “The value of the world's ecosystem services and natural capital”. *Nature*, 387, 253-260.

Constanza, R., Groot, R., Sutton, P., Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S. and Turner, R.K., 2014. “Changes in the global value of ecosystem services”. *Global Environmental Change*, 26, 152-15.

Cotteller, G. and Peerlings J.H.M, 2011. “Spatial planning procedures and property prices: The role of expectations”. *Landscape and Urban Planning*, 100, 77-86.

Couch, C. and Karecha, J., 2006. “Controlling urban sprawl: some experiences from Liverpool”. *Cities*, Vol. 23 (5), 353-363.

Creutzig, F., 2014. “How fuel prices determine public transport infrastructure, modal shares and urban form”. *Urban Climate*, 10, 63-76.

Cunha, A.C., and Melo, J.J., 2007. “Ordenamento do território e finanças locais”. 9ª Conferência Nacional do Ambiente (CNA 2007). Universidade de Aveiro, 18-20.

DGT, 2007a. “Programa Nacional da Política de Ordenamento do Território- Programa de Ação”. DGT (Direção-Geral do Território) Report, September, 2007, 107 pp.

DGT, 2007b. “Programa Nacional da Política de Ordenamento do Território- Relatório”. DGT (Direção-Geral do Território) Report, September 2007, 155 pp.

Dodson, J. and Sipe, N., 2007. “Oil vulnerability in the Australian city: assessing socioeconomic risks from higher urban fuel prices”. *Urban Studies*, 44, 37-62.

EC, 2011. “White Paper, Roadmap to a single European transport area- towards a competitive and resource efficient transport system”. EC report nº144, EC (European Commission), Belgium, Brussels, 32 pp.

EC, 2012. “Possible reforms of real estate taxation: criteria for successful policies”. EC Report, Occasional Papers 119, October 2012, European Commission (EC), Belgium, Brussels, European Economy, 37 pp.

EC, 2014. “Tax reforms in EU Member States”, EC Report, No. 6/2014, European Commission (EC), Belgium, Brussels, European Economy, 156 pp.

EC, 2016. “Taxation trends in the European Union”, EC Report, European Commission (EC), Belgium, Brussels, European Economy, 340 pp.

EEA, 1999. “Environment in the European Union at the turn of the century”. EEA Report, European Environment Agency (EEA), Copenhagen, Denmark, 446 pp.

EEA, 2006a. “The changing faces of Europe’s coastal areas”. EEA Report, No. 6/2006, European Environment Agency (EEA), Copenhagen, Denmark, 112 pp.

EEA, 2006b. “Urban sprawl in Europe- The ignored challenge”, EEA Report, No. 10/2006, European Environment Agency (EEA), Copenhagen, Denmark, 60 pp.

EEA, 2006c. “Using the market for cost-effective environmental policy”. EEA Report No. 1/2006, European Environment Agency (EEA), Copenhagen, Denmark, 48 pp.

EEA, 2009. “Corine Land Cover (CLC2006) 100 m” – version 12/2009. European Environment Agency (EEA), Copenhagen, Denmark. Available at: http://www.eea.europa.eu/data-and-maps/data/corine-land- cover-2006-clc2006-100-m-version-12-2009.

EEA, 2010. “Land in Europe: prices, taxes and use patterns”. EEA Report No. 4/2010, European Environment Agency (EEA), Copenhagen, Denmark, 64 pp.

EEA, 2013a. “A closer look at urban transport”. EEA Report, No. 11/2013, European Environment Agency (EEA), Copenhagen, Denmark, 112 pp.

EEA, 2013b. “Environmental fiscal reform- illustrative potential in Portugal”. EEA Staff Position Note prepared for the conference "Green taxation: a contribution to sustainability", 15 pp.

EEA, 2015. “Evaluating 15 years of transport and environmental policy integration”. EEA Report, No. 7/2015, European Environment Agency (EEA), Copenhagen, Denmark, 84pp.

EEA, 2016. “Urban sprawl in Europe”. Joint EEA-FOEN report No. 11/2016, European Environment Agency (EEA), Copenhagen, Denmark, 140 pp.

Eurostat, 2014. “Taxation trends in the European Union”. Eurostat statistical books, ISSN 1831-8789, 314 pp.

Fidélis, T. and Roebeling, P.C., 2014. “Water resources and land use planning systems in Portugal- Exploring better synergies through Ria de Aveiro”. *Land Use Policy*, 39, 84-95.

FOEN, 2015. “Indicator Urban Sprawl”. Federal Office for the Environment (FOEN), version 26/01/2015, available at: http://www.bafu.admin.ch/umwelt/indikatoren/08611/09514/index.html?lang=em.

Groot, R.S., Alkemade, R., Braat, L., Hein, L. and Willemen, L., 2010. “Challenges in integrating the concept of ecosystem services and values in landscape planning management and decision making”. *Ecological Complexity*, 7, 260-272.

Groot, R.S., Brander, L., Ploeg, S., Constanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., Brink, P. and Beukering, P., 2012. “Global estimates of the value of ecosystems and their services in monetary units”. *Ecosystem Services*, 1, 50-61.

Grossi, D., 2015. “Avaliação dos benefícios económicos e sociais dos espaços verdes/azuis perante as alterações urbanas na cidade de Lyon”. *Master thesis*, Department of Environment and Planning, University of Aveiro, Aveiro, Portugal, 88 pp.

Groves, J.R., 2009. “The impact of positive property tax differentials on the timing of development”. *Regional Science and Urban Economics*, 39, 739-748.

Haase, D. and Schwarz, N., 2009. “Simulation models on human-nature interactions in urban landscapes: a review including spatial economics, system dynamics, cellular automata and agent-based approaches”. *Living Reviews in Landscape Research*, 3, 45 pp.

Hassan, A.M. and Lee, H., 2015. “Toward sustainable development of urban areas: An overview of global trends in trials and policies”. *Land Use Policy*, 48, 199-212.

Henning, E.I., Schwick, C., Soukup, T. and Orlitová E., 2015. “Multi-scale analysis of urban sprawl in Europe: Towards a European de-sprawling strategy”. *Land Use Policy*, 49, 483-498.

INE, 2012. "Anuário Estatístico da Região Centro 2012". ISBN 978-989-25-0217-5, 512 pp.

INE, 2015. "Anuário Estatístico da Região Centro 2015". Instituto Nacional de Estatística, 512 pp.

Institute for Fiscal Studies, 2011. "The taxation of land and property". Tax by Design: The Mirrlees Review, Oxford University Press, UK, Oxford, Chapter 16, 38pp.

Irwin, E.G. and Bockstael, N.E., 2004. "Land use externalities, open space preservation, and urban sprawl". *Regional Science and Urban Economics*, 34, 705-725.

Irwin, E.G., Jayaprakash, C. and Munroe, D.K., 2009. "Towards a comprehensive framework for modeling urban spatial dynamics". *Landscape Ecology*, 24, 1223-1236.

Irwin, E.G., Isserman, A.M., Kilkenny, M. and Partridge, M.D., 2010. "A century of research on rural development and regional issues". *American Journal of Agricultural Economics*, 92(2), 522-553.

Ji, W., Ma., J., Twibell, R.W. and Underhill, K., 2006. "Characterizing urban sprawl using multi-stage remote sensing images and landscape metrics". *Computers, Environment and Urban Systems*, 30, 861-879.

Jou, J. and Lee, T., 2007. "Taxation on land value and development when there are negative externalities from development". *Journal Real Estate Finance Economic*, 36, 103-120.

Kulmer, V., Furst, B., Koland, O., Kafer, A., Steininger K.W., 2014. "The interaction of spatial planning and transport policy: A regional perspective on sprawl". *The Journal of Transport and Land Use*, 7, 57-77.

Lambin, E.F., Rounsevell, M.D.A. and Geist, H.J., 2000. "Are agricultural land-use models able to predict changes in land-use intensity?". *Agriculture Ecosystems & Environment*, 82, 321-331.

Litman, T., 1997. "Full cost accounting of urban tranportation: implications and tools". *Cities*, 14 (3), 169-174.

Milan, B.F., Creutzig, F., 2016. "Municipal policies accelerated urban sprawl and public debts in Spain". *Land Use Policy*, 54, 103-115.

Milan, B.F., Kapfer, D. and Creutzig, F., 2016. "A systematic framework of location value taxes reveals dismal policy design in most European countries". *Land Use Policy*, 51, 335-349.

Mills D.E., 1981. "Growth, speculation and sprawl in a monocentric city". *Journal of Urban Economics*, 10, 201-226.

Ministério do Ambiente, Ordenamento do Território e Energia, 2014. "Reforma Fiscalidade Verde". Governo de Portugal, Ministério do Ambiente, Ordenamento do Território e Energia, 37pp.

Molloy, R. and Shan, H., 2010. “The effect of gasoline prices on household location”. *The Review of Economics and Statistics*, 95, 1212-1221

Morollón, F.R., Marroquin, V.M.G. and Rivero, J.L.P., 2016. “Urban sprawl in Spain: differences among cities and causes”. *European Planning Studies*, 24 (1), 207-226.

Nechyba, T.J. and Walsh, R.P., 2004. “Urban sprawl”. *The Journal of Economic Perspectives*, 18, 177-200.

O’Sullivan A., 2000. “Urban Economics”. 4th Edition, McGraw Hill, New York, USA, 700 pp.

OECD, 2002. “The environmental impact of transport subsidies”. OECD (Organisation for Economic Co-operation and Development) Workshop on Environmentally Harmful Subsidies, Paris, 7-8 Nov. 2002, 33 pp.

Ortuño-Padilla, A. and Fernández-Aracil, P., 2013. “Impact of fuel price on the development of the urban sprawl in Spain”. *Journal of Transport Geography*, 33, 180-187.

Peng, S. and Wang, P., 2009. “A normative analysis of housing-related tax policy in a general equilibrium model of housing quality and prices”. *Journal of Public Economic Theory*, 5, 667-696.

Perman, R., Ma, Y., McGilvray, J. and Common, M., 2003. “Natural Resource and Environmental Economics – Third edition”. *Pearson Education Limited*, Harlow, UK, 699pp.

Pinto, P.M.F., 2008. “Sistema de Apoio à Gestão das Zonas Costeiras- Aplicação de um modelo para simulação do crescimento urbano no trecho Ovar-Mira”. *Master thesis*, Instituto Superior de Estatística e Gestão de Informação da Universidade Nova de Lisboa, Lisboa, Portugal, 112 pp.

Pinto, P., Cabral, P., Caetano, M. and Alves, M.F., 2009. “Urban growth on coastal erosion vulnerable stretches”. *Journal of Coastal Research*, 56, 1567-1571.

Pontius R.G. Jr., Huffaker, D. and Denman, K., 2004. “Useful techniques of validation for spatially explicit” land-change models. *Ecological Modelling*, 179, 445–461.

Prates, J. and Melo, J.J., 2007. “O modelo EcoTerra- instrumentos económicos para melhorar o ordenamento do território”. 9ª Conferência Nacional do Ambiente (CNA 2007), Universidade de Aveiro, 6pp.

Prates, J.C.A. and Melo, J.J., 2009. “Ecoterra model- application of environmental fiscal reform in local government financing in Portugal”. In: Cottrell J, Milne JE, Ashiabor H, Kreiser L, Deketelaere K (Eds), Critical Issues in Environmental Taxation: International and Comparative Perspectives: Volume VI, 699-715. Oxford University Press, UK.

Poelmans, L. and Rompaey, A.V., 2009. “Detecting and modelling spatial patterns of urban sprawl in highly fragmented areas: A case study in the Flanders-Brussels region”. *Landscape and Urban Planning*, 93, 10-19.

Potter, S., Enoch, M., Tom, R., Colin, B. and Barry, U., 2006. “Tax treatment of employer commuting support: an international review”. *Transport Reviews*, 26, 221-237.

PwC, 2014. “Guia Fiscal”. PricewaterhouseCoopers, revised on: 2014/01/10, available at: http://www.pwc.pt/pt/pwcinforfisco/guia-fiscal/2014/imi.html

PwC, 2015. “Guia Fiscal”. PricewaterhouseCoopers, revised on: 2015/01/10, available at: http://www.pwc.pt/pt/pwcinforfisco/guia-fiscal/2015/imi.html

PwC, 2016. “Guia Fiscal”. PricewaterhouseCoopers, revised on: 2016/03/30, available at: http://www.pwc.pt/pt/pwcinforfisco/guia-fiscal/2016/imi.html

Quintão, J., Moreto, M.J. and Soares, A., 2012. “Aveiro- Uma visão integrada da mobilidade urbana”. Município de Aveiro, 25 pp.

Rodriguez, J., 2013. “Effect of high gasoline prices on low-density housing development”. *Leadership and Management in Engineering*, 13, 131-143.

Roebeling, P.C., Fletcher, C.S., Hilbert, D.W. and Udo, J., 2007a. “Welfare gains from urbanizing landscapes in Great Barrier Reef catchments? A spatial environmental-economic modelling approach”. *Sustainable Development and Planning III*, Vols 1 and 2, 737-749.

Roebeling, P.C., Grieken, M.E. and Webster, A.J., 2007b. “Environmental-economic analysis for exploration of efficient land use and land management arrangements, water quality improvement targets and incentives for best management practice adoption in the Tully-Murray catchment”. CSIRO. Sustainable Ecosystems, 32 pp.

Roebeling, P.C., Alves, F.L., Coelho, C.D., Gonçalves, M. and Rocha, J., 2011. “Perda nos valores dos ecossistemas devido à erosão costeira na região da Ria de Aveiro: uma avaliação histórica”. Jornadas da Ria de Aveiro, Universidade de Aveiro, 83-87.

Roebeling, P.C., Saraiva, M., Gnecco, I., Palla, A., Teotónio, C., Alves, H., Rocha, J., Fidélis, T. and Martins, F., 2014a. “Sustainable Urbanizing Landscape Development (SULD) decision support tool: report on other Aqua Cases”. Aqua-Add project, Aqua-Add Technical Report, Vol. 4. Aveiro, Portugal, 56 pp.

Roebeling, P.C., Teotónio, C., Alves, H. and Saraiva, M., 2014b. “Sustainable Urbanizing Landscape Development (SULD) decision support tool: report on frontrunner Aqua Cases”. Aqua-Add project, Aqua-Add Technical Report, Vol. 3. Aveiro, Portugal, 33 pp.

Roebeling, P.C., Fidélis T., Grossi, D., Saraiva, M., Palla, A., Gnecco I., Teotónio, C., and Martins, F., 2016. “Balancing social and economic impacts of nature-based solutions for storm water management”. Proceedings of the 9th NOVATECH International Conference (NOVATECH 2016), 28 June to 1 July 2016, Lyon, France, 4pp.

Roebeling, P.C., Saraiva, M., Palla, A., Gnecco, I., Teotónio, C., Fidelis, T., Martins, F., Alves, H. and Rocha, J., 2017. “Assessing the socio-economic impacts of green/blue space, urban residential and road infrastructure projects in the Confluence (Lyon): a hedonic pricing simulation approach”. *Journal of Environmental Planning and Management*, 18 pp.

Saraiva, M., Roebeling, P.C., Sousa, S., Teotónio, C., Palla, A. and Gnecco, I., 2016. “Dimension of shinkage: Evaluating the socio-economic consequences of population decline in two medium-sized cities in Europe, using the SULD decision support tool". *Environment and Planning B: Planning and Design*, 0(0), 23 pp.

Schindler, M. and Caruso, G., 2014. "Urban compactness and the trade-off between air pollution emission and exposure: lessons from a spatially explicit theoretical model". *Computers, Environment and Urban Systems*, 45, 13-23.

Schlapfer, F., Waltert, F., Segura, L. and Kienast, F., 2015. "Valuation of landscape amenities: a hedonic pricing analysis of housing rents in urban, suburban and periurban Switzerland". *Landscape and Urban* Planning, 141, 24-40.

Sexton, S., Wu, J., and Zilberman, D., 2012. "How high gas prices triggered the housing crisis: theory and empirical evidence". UC Center for Energy and Environmental Economics Working Paper Series, Berkeley, California, 42pp.

Silva, I.J.S.R., 2016. "Assessing the socio-economic impacts of regional plans in the Ria de Aveiro region". *Master thesis*, Department of Environment and Planning, University of Aveiro, Aveiro, Portugal,103 pp.

Silva, J.B., Deus., R.F. and Tenedório, J.A., 2012. "Paying as the urban areas grow- implementing and managing urban development charges using a GIS application". *International Journal of Geographical Information Science*, 26 (9), 1689-1705.

Song, Y. and Zenou, Y., 2006. "Property tax and urban sprawl: Theory and implications for US cities". *Journal of Urban Economics*, 60, 519-534.

Song, Y. and Zenou, Y., 2009. "How do differences in property taxes within cities affect urban sprawl?". *Journal of Regional Science*, 49, 801-831.

Su, Q. and DeSalvo, J.S., 2008. "The effect of transportation subsidies on urban sprawl". *Journal of Regional Science*, 48, 567-594.

Sutton, P.C., 2003. "A scale-adjusted measure of "Urban Sprawl" using nighttime satellite imagery". *Remote Sensing of Environment*, 86, 353-369.

Tanguay, G.A. and Gingras, I., 2011. "Gas prices variations and urban sprawl: an empirical analysis of the 12 largest canadian metropolitan areas". *CIRANO- Scientific Publication*, 29 pp.

Tscharaktschiew, S, and Hirte, G., 2011. "Should subsidies to urban passanger transport be increased? A spatial CGE analysis for a German metropolitan area". *Transport Research*, 46, 285-309.

UA, 2011. "Ocupação dispersa: Custos e Benefícios". Seminário "Ocupação dispersa, Custos e Benefícios", Universidade de Aveiro, Universidade de Évora e DGOTDU, 107 pp.

UA, 2014. "Estratégia de Desenvolvimento Territorial da Região de Aveiro 2014-2020". UA (Universidade de Aveiro) and CIRA (Comunidade Intermunicipal da Região de Aveiro) Joint Report, 159 pp.

Veldkamp, A. and Lambin, E.F., 2001. "Predicting land-use change". *Agriculture Ecosystems and Environment*, 85, 1-6

Wang, Y., Potoglou, D., Orford, S. and Gong, Y., 2015. “Bus stop, property price and land value tax: a multilevel hedonic analysis with quantile calibration”. *Land Use Policy*, 42, 381-391.

Wu, J.J., 2001. “Environmental amenities and the spatial pattern of urban sprawl”. *American Journal of Agricultural Economics*, 83(3), 691-697.

Wu, J.J., 2006. “Environmental amenities, urban sprawl, and community characteristics”. *Journal of Environmental Economics and Management*, 52, 527-547.

Wu, J.J. and Platinga, A.J., 2003. “The influence of public open space on urban spatial structure”. *Journal of Environmental Economics and Management*, 46, 288-309.

Annex

Annex 1. Complete flat property tax simulation results.

Variable	Base	2.5% Property Tax		5% Property Tax		10% Property Tax	
Land use:							
Forest (ha)	230	230	0.0%	230	0.0%	230	0.0%
Water (ha)	156	156	0.0%	156	0.0%	156	0.0%
Agriculture (ha)	986	999	1.3%	1011	2.5%	1032	4.7%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	42	-2.7%	41	-5.1%	39	-9.9%
Res2 (ha)	254	244	-4.0%	234	-7.8%	217	-14.5%
Res3 (ha)	36	34	-4.5%	33	-8.0%	30	-15.3%
Total (ha)	333	321	-3.9%	309	-7.5%	287	-13.9%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Population:							
Res1	4929	4929	0.0%	4929	0.0%	4929	0.0%
Res2	18046	18046	0.0%	18046	0.0%	18046	0.0%
Res3	3103	3103	0.0%	3103	0.0%	3103	0.0%
Total	26078	26078	0.0%	26078	0.0%	26078	0.0%
Development density:							
Res1 (1000m^2)	182.6	178.0	-2.5%	173.7	-4.9%	165.6	-9.3%
Res2 (1000m^2)	1257.6	1221.2	-2.9%	1186.3	-5.7%	1123.2	-10.7%
Res3 (1000m^2)	357.0	345.8	-3.1%	336.1	-5.8%	317.0	-11.2%
Total (1000m^2)	1797.1	1745.0	-2.9%	1696.2	-5.6%	1605.8	-10.6%
Housing quantity:							
Res1 (1000m^2)	63.4	60.1	-5.2%	57.2	-9.8%	51.8	-18.3%
Res2 (1000m^2)	695.0	647.1	-6.9%	602.6	-13.3%	528.1	-24.0%
Res3 (1000m^2)	158.8	147.0	-7.4%	137.8	-13.3%	119.8	-24.6%
Total (1000m^2)	917.2	854.2	-6.9%	797.6	-13.0%	699.7	-23.7%
Living space:							
Res1 (m^2/hh)	88.5	86.3	-2.5%	84.2	-4.9%	80.3	-9.3%
Res2 (m^2/hh)	166.6	161.7	-2.9%	157.1	-5.7%	148.7	-10.7%
Res3 (m^2/hh)	274.9	266.3	-3.1%	258.9	-5.8%	244.2	-11.2%
Average (m^2/hh)	164.7	159.9	-2.9%	155.5	-5.6%	147.2	-10.6%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.8	2.6%	25.4	5.2%	26.7	10.4%
Res2 (€/m^2/yr)	26.3	27.1	3.1%	27.9	6.3%	29.5	12.5%
Res3 (€/m^2/yr)	37.4	38.6	3.2%	39.7	6.2%	42.1	12.6%
Average (€/m^2/yr)	27.2	28.0	3.0%	28.8	6.1%	30.5	12.1%
Total (m€/yr)	50.8	50.8	0.1%	50.9	0.2%	50.9	0.3%
Floors:							
Res1	2.9	3.0	2.8%	3.0	5.5%	3.2	11%
Res2	1.8	1.8	4.3%	2.0	8.8%	2.1	17.5%
Res3	2.2	2.4	4.6%	2.4	8.6%	2.6	17.8%

Annex 2. Complete linear property tax; 5% and 10% flat property tax simulation results.

Variable	Base	Linear 5%-10% Property Tax		Linear 10%-5% Property Tax		5% Property Tax		10% Property Tax	
Land use:									
Forest (ha)	230	230	0.0%	230	0.0%	230	0.0%	230	0.0%
Water (ha)	156	156	0.0%	156	0.0%	156	0.0%	156	0.0%
Agriculture (ha)	986	1028	4.3%	1014	2.8%	1011	2.5%	1032	4.7%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%	128	0.0%
Urban									
Res1 (ha)	44	39	-9.7%	41	-5.4%	41	-5.1%	39	-9.9%
Res2 (ha)	254	219	-14.0%	238	-6.2%	234	-7.8%	217	-14.5%
Res3 (ha)	36	33	-8.1%	26	-27.5%	33	-8.0%	30	-15.3%
Total (ha)	333	291	-12.8%	305	-8.4%	309	-7.5%	287	-13.9%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%	2139	0.0%
Population:									
Res1	4929	4929	0.0%	4929	0.0%	4929	0.0%	4929	0.0%
Res2	18046	18046	0.0%	18046	0.0%	18046	0.0%	18046	0.0%
Res3	3103	3103	0.0%	3103	0.0%	3103	0.0%	3103	0.0%
Total	26078	26078	0.0%	26078	0.0%	26078	0.0%	26078	0.0%
Development density:									
Res1 (1000m^2)	182.6	166.2	-9.0%	173.0	-5.2%	173.7	-4.9%	165.6	-9.3%
Res2 (1000m^2)	1257.6	1133.0	-9.9%	1183.9	-5.9%	1186.3	-5.7%	1123.2	-10.7%
Res3 (1000m^2)	357.0	330.2	-7.5%	307.0	-14.0%	336.1	-5.8%	317.0	-11.2%
Total (1000m^2)	1797.1	1629.4	-9.3%	1664.0	-7.4%	1696.2	-5.6%	1605.8	-10.6%
Housing quantity:									
Res1 (1000m^2)	63.4	52.0	-17.9%	56.8	-10.4%	57.2	-9.8%	51.8	-18.3%
Res2 (1000m^2)	695.0	535.6	-22.9%	612.5	-11.9%	602.6	-13.3%	528.1	-24.0%
Res3 (1000m^2)	158.8	134.8	-15.1%	99.8	-37.1%	137.8	-13.3%	119.8	-24.6%
Total (1000m^2)	917.2	722.5	-21.2%	769.1	-16.1%	797.6	-13.0%	699.7	-23.7%
Living space:									
Res1 (m^2/hh)	88.5	80.6	-9.0%	83.9	-5.2%	84.2	-4.9%	80.3	-9.3%
Res2 (m^2/hh)	166.6	150.1	-9.9%	156.8	-5.9%	157.1	-5.7%	148.7	-10.7%
Res3 (m^2/hh)	274.9	254.3	-7.5%	236.5	-14.0%	258.9	-5.8%	244.2	-11.2%
Average (m^2/hh)	164.7	149.3	-9.3%	152.5	-7.4%	155.5	-5.6%	147.2	-10.6%
Real estate value:									
Res1 (€/m^2/yr)	24.2	26.6	10.0%	25.5	5.6%	25.4	5.2%	26.7	10.4%
Res2 (€/m^2/yr)	26.3	29.3	11.5%	27.9	6.4%	27.9	6.3%	29.5	12.5%
Res3 (€/m^2/yr)	37.4	40.4	8.2%	43.4	16.1%	39.7	6.2%	42.1	12.6%
Average (€/m^2/yr)	27.2	30.2	11.1%	28.9	6.4%	28.8	6.1%	30.5	12.1%
Total (m€/yr)	50.8	51.0	0.4%	50.8	0.0%	50.9	0.2%	50.9	0.3%
Floors:									
Res1	2.9	3.2	10.9%	3.0	5.8%	3.0	5.5%	3.2	11%
Res2	1.8	2.1	16.9%	1.9	6.8%	2.0	8.8%	2.1	17.5%
Res3	2.2	2.4	9.0%	3.1	36.9%	2.4	8.6%	2.6	17.8%

Annex 3. Complete flat land tax simulation results.

Variable	Base	50% Land Tax		100% Land Tax		200% Land Tax	
Land use:							
Forest (ha)	230	230	0.0%	230	0.0%	230	0.0%
Water (ha)	156	156	0.0%	156	0.0%	156	0.0%
Agriculture (ha)	986	986	0.0%	986	0.0%	986	0.0%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	44	-0.1%	44	-0.1%	44	-0.1%
Res2 (ha)	254	253	-0.3%	253	-0.4%	253	-0.5%
Res3 (ha)	36	36	1.5%	37	2.1%	37	2.7%
Total (ha)	333	333	-0.1%	333	-0.1%	333	-0.1%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Population:							
Res1	4929	4929	0.0%	4929	0.0%	4929	0.0%
Res2	18046	18046	0.0%	18046	0.0%	18046	0.0%
Res3	3103	3103	0.0%	3103	0.0%	3103	0.0%
Total	26078	26078	0.0%	26078	0.0%	26078	0.0%
Development density:							
Res1 ($1000m^2$)	182.6	182.6	0.0%	182.6	0.0%	182.6	0.0%
Res2 ($1000m^2$)	1257.6	1256.5	-0.1%	1256.5	-0.1%	1255.5	-0.2%
Res3 ($1000m^2$)	357.0	358.7	0.5%	359.4	0.7%	360.1	0.9%
Total ($1000m^2$)	1797.1	1797.7	0.0%	1798.0	0.0%	1798.2	0.1%
Housing quantity:							
Res1 ($1000m^2$)	63.4	63.3	-0,1%	63.3	-0.1%	63.3	-0.1%
Res2 ($1000m^2$)	695.0	692.0	-0.4%	690.7	-0.6%	689.5	-0.8%
Res3 ($1000m^2$)	158.8	161.8	1.9%	163.0	2.7%	164.3	3.5%
Total ($1000m^2$)	917.2	917.2	0.0%	917.1	0.0%	917.2	0.0%
Living space:							
Res1 (m^2/hh)	88.5	88.5	0.0%	88.5	0.0%	88.5	0.0%
Res2 (m^2/hh)	166.6	166.4	-0.1%	166.3	-0.1%	166.3	-0.2%
Res3 (m^2/hh)	274.9	276.3	0.5%	276.8	0.7%	277.4	0.9%
Average (m^2/hh)	164.7	164.8	0.0%	164.8	0.0%	164.8	0.1%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.2	0.0%	24.2	0.0%	24.2	0.0%
Res2 (€/m^2/yr)	26.3	26.3	0.1%	26.3	0.2%	26.3	0.2%
Res3 (€/m^2/yr)	37.4	37.2	-0.5%	37.1	-0.7%	37.1	-0.9%
Average (€/m^2/yr)	27.2	27.2	0.1%	27.2	0.1%	27.2	0.1%
Total (m€/yr)	50.8	50.8	0.0%	50.8	0.0%	50.8	0.0%
Floors:							
Res1	2.9	2.9	0.1%	2.9	0.1%	2.9	0.1%
Res2	1.8	1.8	0.3%	1.8	0.5%	1.8	0.6%
Res3	2.2	2.2	-1.4%	2.2	-1.9%	2.2	-2.5%

Annex 4. Complete linearly increasing land tax simulation results.

Variable	Base	100€/Km Land Tax		300€/Km Land Tax		500€/Km Land Tax	
Land use:							
Forest (ha)	230	230	0.0%	230	0.0%	230	0.0%
Water (ha)	156	156	0.0%	156	0.0%	156	0.0%
Agriculture (ha)	986	986	0.0%	979	-0.7%	978	-0.8%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	44	-0.1%	45	2.8%	45	3.6%
Res2 (ha)	254	253	-0.4%	262	3.3%	263	3.7%
Res3 (ha)	36	37	2.1%	33	-8.8%	32	-9.6%
Total (ha)	333	333	-0.1%	340	1.9%	341	2.2%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Population:							
Res1	4929	4929	0.0%	4929	0.0%	4929	0.0%
Res2	18046	18046	0.0%	18046	0.0%	18046	0.0%
Res3	3103	3103	0.0%	3103	0.0%	3103	0.0%
Total	26078	26078	0.0%	26078	0.0%	26078	0.0%
Development density:							
Res1 (1000m^2)	182.6	182.6	0.0%	183.8	0.6%	184.1	0.8%
Res2 (1000m^2)	1257.6	1256.0	-0.1%	1259.3	0.9%	1270.5	1.0%
Res3 (1000m^2)	357.0	359.4	0.7%	346.4	-3.0%	345.4	-3.2%
Total (1000m^2)	1797.1	1798.0	0.0%	1799.4	0.1%	1799.9	0.2%
Housing quantity:							
Res1 (1000m^2)	63.4	63.4	0.0%	63.3	4.6%	67.2	6.0%
Res2 (1000m^2)	695.0	694.2	-0.1%	729.5	5.0%	733.4	5.5%
Res3 (1000m^2)	158.8	159.6	0.5%	141.2	-11.1%	139.6	-12.1%
Total (1000m^2)	917.2	917.2	0.0%	937.1	2.2%	940.3	2.5%
Living space:							
Res1 (m^2/hh)	88.5	88.5	0.0%	89.1	0.6%	89.3	0.8%
Res2 (m^2/hh)	166.6	166.3	-0.1%	168.1	0.9%	168.3	1.0%
Res3 (m^2/hh)	274.9	276.8	0.7%	266.8	-3.0%	266.0	-3.2%
Average (m^2/hh)	164.7	164.8	0.0%	164.9	0.1%	165.0	0.2%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.2	0.0%	23.9	-1.2%	23.8	-1.6%
Res2 (€/m^2/yr)	26.3	26.3	0.2%	25.9	-1.3%	25.9	-1.4%
Res3 (€/m^2/yr)	37.4	37.1	-0.7%	38.5	3.1%	38.6	3.4%
Average (€/m^2/yr)	27.2	27.2	0.1%	26.9	-1.2%	26.8	-1.3%
Total (m€/yr)	50.8	50.8	0.0%	50.6	-0.3%	50.6	-0.3%
Floors:							
Res1	2.9	2.9	0.1%	2.8	-3.8%	2.7	-4.9%
Res2	1.8	1.8	0.5%	1.7	-3.8%	1.7	-4.3%
Res3	2.2	2.2	-1.9%	2.5	9.1%	2.5	10.1%

Annex 5. Complete low income household public transport subsidy simulation results.

Variable	Base	10% Transport Subsidy		25% Transport Subsidy		50% Transport Subsidy	
Land use:							
Forest (ha)	230	230	0.0%	230	0.0%	230	0.0%
Water (ha)	156	156	0.0%	156	0.0%	156	0.0%
Agriculture (ha)	986	988	0.2%	991	0.6%	996	1.1%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	43	-2.2%	42	-4.1%	66	51.7%
Res2 (ha)	254	253	-0.5%	251	-1.3%	222	-12.7%
Res3 (ha)	36	36	-0.4%	36	-0.8%	35	-2.1%
Total (ha)	333	331	-0.7%	328	-1.6%	323	-3.1%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Population:							
Res1	4929	4929	0.0%	4929	0.0%	4929	0.0%
Res2	18046	18046	0.0%	18046	0.0%	18046	0.0%
Res3	3103	3103	0.0%	3103	0.0%	3103	0.0%
Total	26078	26078	0.0%	26078	0.0%	26078	0.0%
Development density:							
Res1 (1000m^2)	182.6	181.5	-0.6%	180.7	-1.1%	210.6	15.3%
Res2 (1000m^2)	1257.6	1255.8	-0.1%	1252.4	-0.4%	1180.1	-3.8%
Res3 (1000m^2)	357.0	356.4	-0.1%	356.0	-0.3%	354.4	0.7%
Total (1000m^2)	1797.1	1793.8	-0.2%	1789.0	-0.5%	1774.2	-1.3%
Housing quantity:							
Res1 (1000m^2)	63.4	61.7	-2.7%	60.3	-5.0%	108.2	70.6%
Res2 (1000m^2)	695.0	690.7	-0.6%	682.4	-1.8%	577.4	-16.9%
Res3 (1000m^2)	158.8	157.9	-0.5%	157.1	-1.0%	154.4	-2.8%
Total (1000m^2)	917.2	910.3	-0.8%	899.8	-1.9%	840.0	-8.4%
Living space:							
Res1 (m^2/hh)	88.5	88.0	-0.6%	87.6	-1.1%	102.1	15.3%
Res2 (m^2/hh)	166.6	166.3	-0.1%	165.9	-0.4%	160.1	-3.8%
Res3 (m^2/hh)	274.9	274.5	-0.1%	274.2	-0.3%	273.0	-0.7%
Average (m^2/hh)	164.7	164.4	-0.2%	164.0	-0.5%	162.6	-1.3%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.4	0.8%	24.5	1.6%	21.2	-12.4%
Res2 (€/m^2/yr)	26.3	26.3	0.2%	26.4	0.5%	27.6	5.1%
Res3 (€/m^2/yr)	37.4	37.4	0.1%	37.5	0.3%	37.6	0.7%
Average (€/m^2/yr)	27.2	27.3	0.3%	27.4	0.6%	27.4	0.7%
Total (m€/yr)	50.8	50.8	0.0%	50.8	0.1%	51.2	0.8%
Floors:							
Res1	2.9	2.9	2.2%	3.0	4.1%	1.9	-32.4%
Res2	1.8	1.8	0.5%	1.8	1.4%	2.1	15.7%
Res3	2.2	2.3	0.4%	2.3	0.8%	2.3	2.1%

Annex 6. Complete low and middle income household public transport subsidy simulation results.

Variable	Base	10% Transport Subsidy		25% Transport Subsidy		50% Transport Subsidy	
Land use:							
Forest (ha)	230	230	0.0%	230	0.0%	230	0.0%
Water (ha)	156	156	0.0%	156	0.0%	156	0.0%
Agriculture (ha)	986	1000	1.4%	1019	3.3%	1047	6.2%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%	128	0.0%
Urban							
Res1 (ha)	44	42	-2.6%	41	-6.9%	38	-13.0%
Res2 (ha)	254	243	-4.5%	231	-8.9%	213	-16.0%
Res3 (ha)	36	34	-3.9%	29	-20.1%	21	-40.7%
Total (ha)	333	320	-4.2%	301	-9.9%	273	-18.3%
Total	2139	2139	0.0%	2139	0.0%	2139	0.0%
Population:							
Res1	4929	4929	0.0%	4929	0.0%	4929	0.0%
Res2	18046	18046	0.0%	18046	0.0%	18046	0.0%
Res3	3103	3103	0.0%	3103	0.0%	3103	0.0%
Total	26078	26078	0.0%	26078	0.0%	26078	0.0%
Development density:							
Res1 (1000m^2)	182.6	181.3	-0.7%	179.1	-1.9%	176.1	-3.6%
Res2 (1000m^2)	1257.6	1241.6	-1.3%	1226.1	-2.5%	1199.8	-4.6%
Res3 (1000m^2)	357.0	352.0	-1.4%	330.5	-7.4%	303.0	-15.1%
Total (1000m^2)	1797.1	1774.9	-1.2%	1735.7	-3.4%	1678.9	-6.6%
Housing quantity:							
Res1 (1000m^2)	63.4	61.3	-3.3%	57.8	-8.9%	52.8	-16.7%
Res2 (1000m^2)	695.0	653.8	-5.9%	614.0	-11.7%	550.7	-20.8%
Res3 (1000m^2)	158.8	150.9	-5.0%	118.6	-25.3%	79.4	-50.0%
Total (1000m^2)	917.2	866.0	-5.6%	790.4	-13.8%	683.0	-25.5%
Living space:							
Res1 (m^2/hh)	88.5	87.9	-0.7%	86.9	-1.9%	85.4	-3.6%
Res2 (m^2/hh)	166.6	164.4	-1.3%	162.4	-2.5%	158.9	-4.6%
Res3 (m^2/hh)	274.9	271.1	-1.4%	254.6	-7.4%	233.4	-15.1%
Average (m^2/hh)	164.7	162.7	-1.2%	159.1	-3.4%	153.9	-6.6%
Real estate value:							
Res1 (€/m^2/yr)	24.2	24.4	1.0%	24.8	2.7%	25.5	5.4%
Res2 (€/m^2/yr)	26.3	26.7	1.7%	27.2	3.6%	28.0	6.8%
Res3 (€/m^2/yr)	37.4	37.8	1.2%	40.2	7.5%	44.8	19.8%
Average (€/m^2/yr)	27.2	27.6	1.6%	28.1	3.4%	29.0	6.7%
Total (m€/yr)	50.8	50.9	0.3%	51.1	0.6%	51.7	1.8%
Floors:							
Res1	2.9	3.0	2.7%	3.1	7.6%	3.3	15.8%
Res2	1.8	1.9	5.0%	2.0	10.4%	2.2	20.4%
Res3	2.2	2.3	3.8%	2.8	23.9%	3.8	69.8%

Annex 7. 10% public transport subsidy for each type of household simulation results.

Variable	Base	10% - Lower households		10% - Lower and Medium households	
Land use:					
Forest (ha)	230	230	0.0%	230	0.0%
Water (ha)	156	156	0.0%	156	0.0%
Agriculture (ha)	986	988	0.2%	1000	1.4%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%
Urban					
Res1 (ha)	44	43	-2.2%	42	-2.6%
Res2 (ha)	254	253	-0.5%	243	-4.5%
Res3 (ha)	36	36	-0.4%	34	-3.9%
Total (ha)	333	331	-0.7%	320	-4.2%
Total	2139	2139	0.0%	2139	0.0%
Population:					
Res1	4929	4929	0.0%	4929	0.0%
Res2	18046	18046	0.0%	18046	0.0%
Res3	3103	3103	0.0%	3103	0.0%
Total	26078	26078	0.0%	26078	0.0%
Development density:					
Res1 ($1000m^2$)	182.6	181.5	-0.6%	181.3	-0.7%
Res2 ($1000m^2$)	1257.6	1255.8	-0.1%	1241.6	-1.3%
Res3 ($1000m^2$)	357.0	356.4	-0.1%	352.0	-1.4%
Total ($1000m^2$)	1797.1	1793.8	-0.2%	1774.9	-1.2%
Housing quantity:					
Res1 ($1000m^2$)	63.4	61.7	-2.7%	61.3	-3.3%
Res2 ($1000m^2$)	695.0	690.7	-0.6%	653.8	-5.9%
Res3 ($1000m^2$)	158.8	157.9	-0.5%	150.9	-5.0%
Total ($1000m^2$)	917.2	910.3	-0.8%	866.0	-5.6%
Living space:					
Res1 (m^2/hh)	88.5	88.0	-0.6%	87.9	-0.7%
Res2 (m^2/hh)	166.6	166.3	-0.1%	164.4	-1.3%
Res3 (m^2/hh)	274.9	274.5	-0.1%	271.1	-1.4%
Average (m^2/hh)	164.7	164.4	-0.2%	162.7	-1.2%
Real estate value:					
Res1 (€/m^2/yr)	24.2	24.4	0.8%	24.4	1.0%
Res2 (€/m^2/yr)	26.3	26.3	0.2%	26.7	1.7%
Res3 (€/m^2/yr)	37.4	37.4	0.1%	37.8	1.2%
Average (€/m^2/yr)	27.2	27.3	0.3%	27.6	1.6%
Total (m€/yr)	50.8	50.8	0.0%	50.9	0.3%
Floors:					
Res1	2.9	2.9	2.2%	3.0	2.7%
Res2	1.8	1.8	0.5%	1.9	5.0%
Res3	2.2	2.3	0.4%	2.3	3.8%

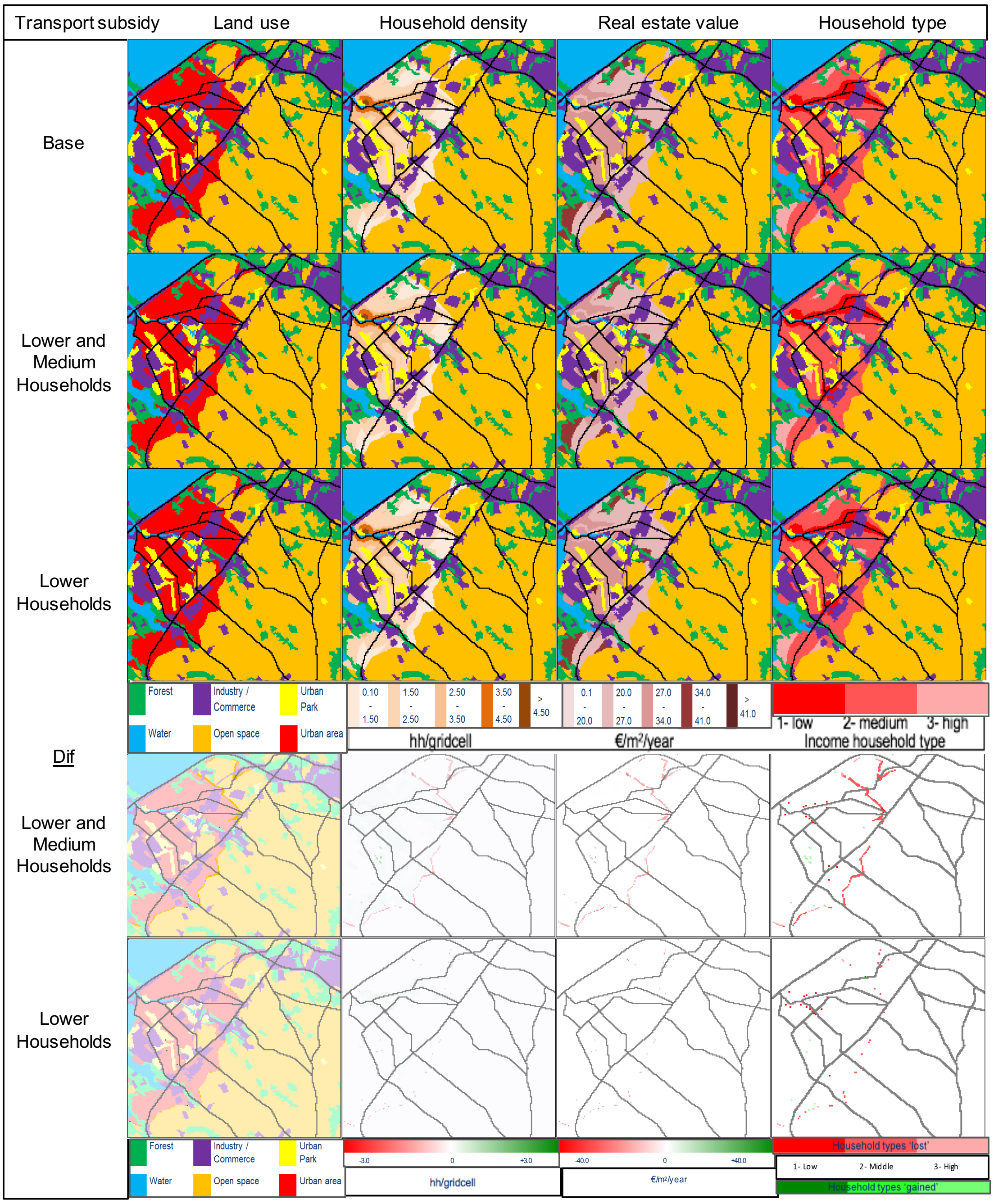
Annex 8. 25% public transport subsidy for each type of household simulation results.

Variable	Base	25% - Lower households		25% - Lower and Medium households	
Land use:					
Forest (ha)	230	230	0.0%	230	0.0%
Water (ha)	156	156	0.0%	156	0.0%
Agriculture (ha)	986	991	0.6%	1019	3.3%
Industry/Commerce (ha)	250	250	0.0%	250	0.0%
Urban park (ha)	56	56	0.0%	56	0.0%
Roads (ha)	128	128	0.0%	128	0.0%
Urban					
Res1 (ha)	44	42	-4.1%	41	-6.9%
Res2 (ha)	254	251	-1.3%	231	-8.9%
Res3 (ha)	36	36	-0.8%	29	-20.1%
Total (ha)	333	328	-1.6%	301	-9.9%
Total	2139	2139	0.0%	2139	0.0%
Population:					
Res1	4929	4929	0.0%	4929	0.0%
Res2	18046	18046	0.0%	18046	0.0%
Res3	3103	3103	0.0%	3103	0.0%
Total	26078	26078	0.0%	26078	0.0%
Development density:					
Res1 (1000m^2)	182.6	180.7	-1.1%	179.1	-1.9%
Res2 (1000m^2)	1257.6	1252.4	-0.4%	1226.1	-2.5%
Res3 (1000m^2)	357.0	356.0	-0.3%	330.5	-7.4%
Total (1000m^2)	1797.1	1789.0	-0.5%	1735.7	-3.4%
Housing quantity:					
Res1 (1000m^2)	63.4	60.3	-5.0%	57.8	-8.9%
Res2 (1000m^2)	695.0	682.4	-1.8%	614.0	-11.7%
Res3 (1000m^2)	158.8	157.1	-1.0%	118.6	-25.3%
Total (1000m^2)	917.2	899.8	-1.9%	790.4	-13.8%
Living space:					
Res1 (m^2/hh)	88.5	87.6	-1.1%	86.9	-1.9%
Res2 (m^2/hh)	166.6	165.9	-0.4%	162.4	-2.5%
Res3 (m^2/hh)	274.9	274.2	-0.3%	254.6	-7.4%
Average (m^2/hh)	164.7	164.0	-0.5%	159.1	-3.4%
Real estate value:					
Res1 (€/m^2/yr)	24.2	24.5	1.6%	24.8	2.7%
Res2 (€/m^2/yr)	26.3	26.4	0.5%	27.2	3.6%
Res3 (€/m^2/yr)	37.4	37.5	0.3%	40.2	7.5%
Average (€/m^2/yr)	27.2	27.4	0.6%	28.1	3.4%
Total (m€/yr)	50.8	50.8	0.1%	51.1	0.6%
Floors:					
Res1	2.9	3.0	4.1%	3.1	7.6%
Res2	1.8	1.8	1.4%	2.0	10.4%
Res3	2.2	2.3	0.8%	2.8	23.9%

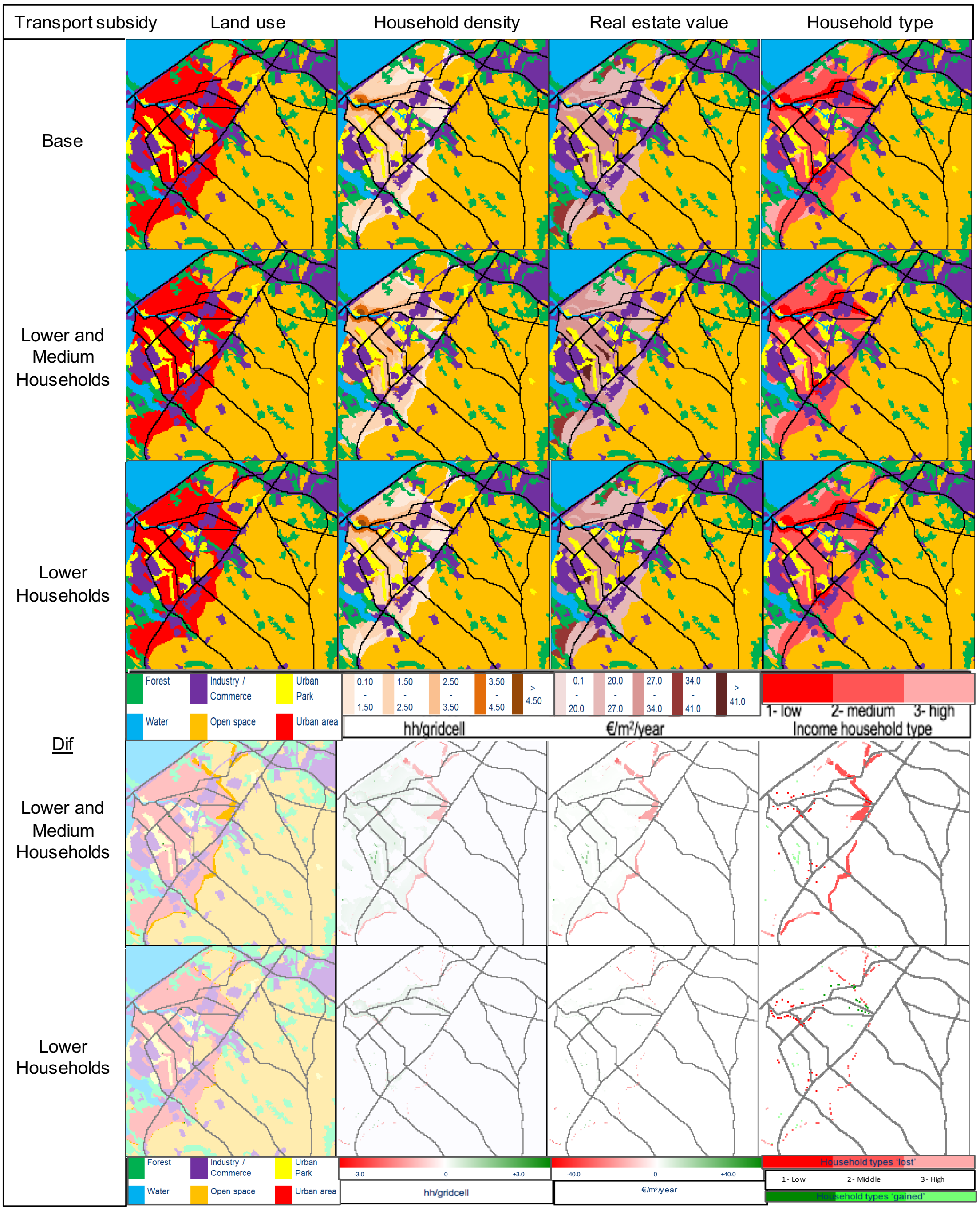
Annex 9. 50% public transport subsidy for each type of household simulation results.

Variable	Base	50% - Lower households		50% - Lower and Medium households		
Land use:						
Forest (ha)	230	230	0.0%	230	0.0%	230
Water (ha)	156	156	0.0%	156	0.0%	156
Agriculture (ha)	986	996	1.1%	1047	6.2%	1051
Industry/Commerce (ha)	250	250	0.0%	250	0.0%	250
Urban park (ha)	56	56	0.0%	56	0.0%	56
Roads (ha)	128	128	0.0%	128	0.0%	128
Urban						
Res1 (ha)	44	66	51.7%	38	-13.0%	37
Res2 (ha)	254	222	-12.7%	213	-16.0%	202
Res3 (ha)	36	35	-2.1%	21	-40.7%	29
Total (ha)	333	323	-3.1%	273	-18.3%	268
Total	2139	2139	0.0%	2139	0.0%	2139
Population:						
Res1	4929	4929	0.0%	4929	0.0%	4929
Res2	18046	18046	0.0%	18046	0.0%	18046
Res3	3103	3103	0.0%	3103	0.0%	3103
Total	26078	26078	0.0%	26078	0.0%	26078
Development density:						
Res1 (1000m^2)	182.6	210.6	15.3%	176.1	-3.6%	175.7
Res2 (1000m^2)	1257.6	1180.1	-3.8%	1199.8	-4.6%	1180.1
Res3 (1000m^2)	357.0	354.4	0.7%	303.0	-15.1%	332.6
Total (1000m^2)	1797.1	1774.2	-1.3%	1678.9	-6.6%	1687.4
Housing quantity:						
Res1 (1000m^2)	63.4	108.2	70.6%	52.8	-16.7%	51.1
Res2 (1000m^2)	695.0	577.4	-16.9%	550.7	-20.8%	513.8
Res3 (1000m^2)	158.8	154.4	-2.8%	79.4	-50.0%	118.4
Total (1000m^2)	917.2	840.0	-8.4%	683.0	-25.5%	683.4
Living space:						
Res1 (m^2/hh)	88.5	102.1	15.3%	85.4	-3.6%	84.7
Res2 (m^2/hh)	166.6	160.1	-3.8%	158.9	-4.6%	156.3
Res3 (m^2/hh)	274.9	273.0	-0.7%	233.4	-15.1%	256.1
Average (m^2/hh)	164.7	162.6	-1.3%	153.9	-6.6%	154.6
Real estate value:						
Res1 (€/m^2/yr)	24.2	21.2	-12.4%	25.5	5.4%	25.7
Res2 (€/m^2/yr)	26.3	27.6	5.1%	28.0	6.8%	28.6
Res3 (€/m^2/yr)	37.4	37.6	0.7%	44.8	19.8%	40.4
Average (€/m^2/yr)	27.2	27.4	0.7%	29.0	6.7%	29.4
Total (m€/yr)	50.8	51.2	0.8%	51.7	1.8%	51.6
Floors:						
Res1	2.9	1.9	-32.4%	3.3	15.8%	3.4
Res2	1.8	2.1	15.7%	2.2	20.4%	2.3
Res3	2.2	2.3	2.1%	3.8	69.8%	2.8

Annex 10. 10% public transport subsidy for each type of household simulation results (maps).



Annex 11. 25% public transport subsidy for each type of household simulation results (maps).



Annex 12. 50% public transport subsidy for each type of household simulation results (maps).